December 2002

Sacramento and San Joaquin River Basins

Comprehensive Study

TECHNICAL STUDIES DOCUMENTATION

APPENDIX A

INFORMATION PAPERS

US Army Corps of Engineers
Sacramento District

APPENDIX A
INFORMATION PAPERS

This appendix includes a collection of short, informational papers and technical memoranda relating to various technical issues encountered during the Comprehensive Study. The purpose of the information papers varies, from documenting research or findings about key planning topics to providing simplified summaries of complex technical issues. These papers are for informational purposes only and do not intend to recommend or promote specific flood damage reduction or environmental restoration measures, indicate the importance of specific issues, or represent every issue brought to the attention of the study. Instead, they document information and preliminary findings that may be useful for future studies. The information papers included in this appendix are listed below, in the order of appearance:

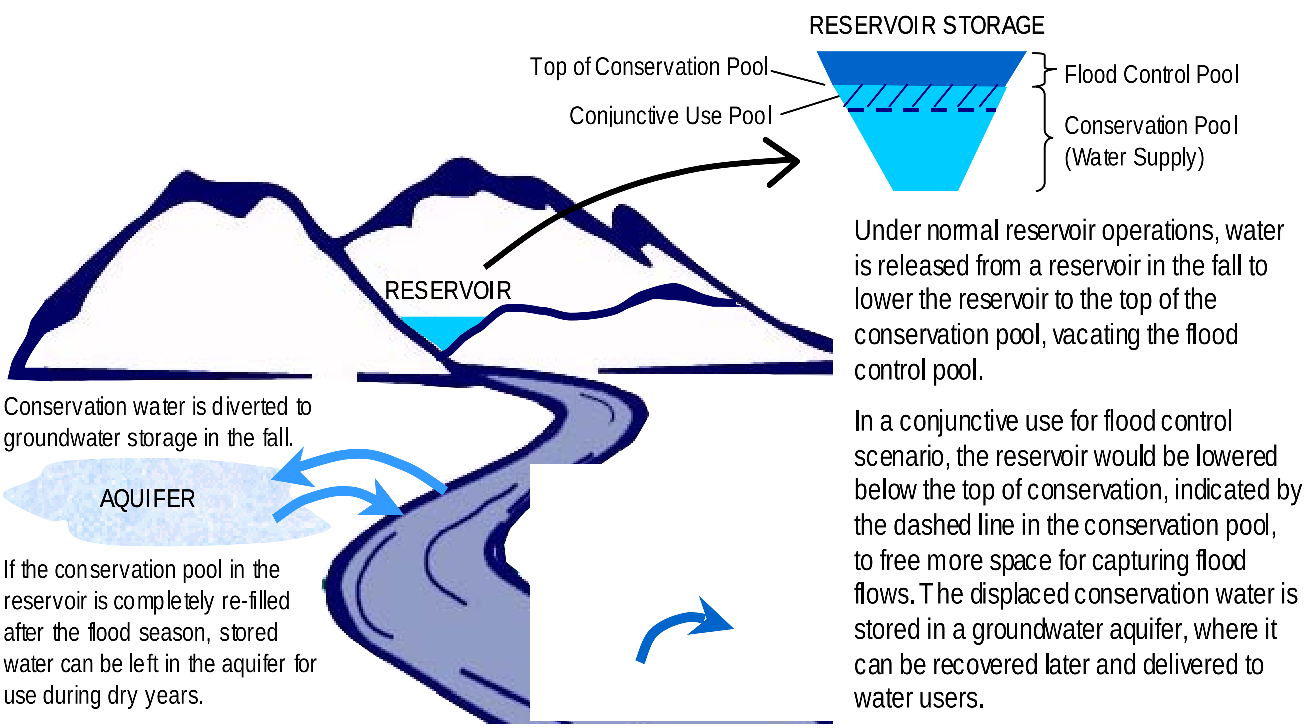
- Conjunctive Use for Flood Control
- Upper Sacramento River HEC-RAS Model
- Preliminary Simulation of Flood Conditions in the Sacramento - San Joaquin Delta
- Global Warming
- Subsidence in the Central Valley
- Technical Evaluation Process
- Vegetation and the Flood Management System

COMPREHENSIVE STUDY INFORMATION PAPER:

CONJUNCTIVE USE FOR FLOOD PROTECTION

Conjunctive Use is the cooperative management of both surface water (reservoirs, rivers, and canals) and groundwater (aquifer) resources to expand the utility of both systems. While flood protection might not be the first priority of conjunctive use operations in California, the U.S. Army Corps of Engineer's Hydrologic Engineering Center (HEC), at the request of the Comprehensive Study, pursued an investigation that evaluated conjunctive use reservoir operations focused on providing guaranteed flood protection.

Under normal operating conditions, reservoirs make releases in the fall to vacate the flood control pool and make room for storing flood flows, bringing the reservoir to the top of the conservation (water supply) pool. With conjunctive use operations aimed to increase flood protection, the reservoir storage level is lowered below the flood control pool, and the displaced conservation water is transferred to groundwater storage. This transfer not only vacates additional space in the reservoir to intercept seasonal flood flows, but also conserves that water in another location. Thus, the "conjunctive use pool" represents reservoir volume that serves the dual purpose of flood protection and conservation storage. The conjunctive use pool is transferred to groundwater via groundwater injection wells or recharge (percolation) basins. Suitable aquifers for conjunctive use operations are those that are overdrawn and thus have room for storage, those that have recharge potential, those that are in proximity to a reservoir or river, and those that are in proximity to the water users.



HEC developed a conceptual model to represent conjunctive use reservoir-aquifer operations focused on maximizing guaranteed flood protection. The conceptual model simulates transfers between reservoirs, aquifers, agricultural demand, and additional end users within six sub-basins. The sub-basins were selected based on the need for additional reservoir flood control space and the presence of favorable aquifer sites downstream from the reservoirs. The sub-basins are:

1. Oroville Reservoir on the Feather River
2. New Bullards Bar Reservoir on the Yuba River
3. Folsom Reservoir on the American River
4. New Don Pedro Reservoir on the Tuolumne River
5. Lake McClure (New Exchequer Dam) on the Merced River
6. Millerton Lake (Friant Dam) on the San Joaquin River

HEC used the conceptual model to size the optimal conjunctive use pool in each reservoir and determine the amount of new yield generated from conjunctive use operations considering four infrastructure scenarios. These scenarios were:

Scenario #1 (Maximum Infrastructure) - maximum amount of space in the recharge basin and uses full-sized recharge rate at each aquifer site.

Scenario #2 (Half-Size Recharge Basins) – uses only half of the recharge basin assumed for Scenario #1, but still uses full recharge/extraction rate.

Scenario #3 (Reduced Canal Capacity) – River to aquifer conveyance capacity is reduced but uses a full sized recharge basin.

Scenario #4 (Minimum Infrastructure) – Minimum level of infrastructure needed, assumes half of the recharge basin and reduced river to aquifer conveyance capacity.

TABLE 1
ADDITIONAL FLOOD STORAGE AND YIELD FROM CONJUNCTIVE USE

Reservoir	Normal Flood Pool (10^3 ac-ft)	Additional CU Pool		Volume of New Yield			
		Scenario 1,3 (10^3 ac-ft)	Scenario 2,4 (10^3 ac-ft)	Scenario 1 (10^3 ac-ft)	Scenario 2 (10^3 ac-ft)	Scenario 3 (10^3 ac-ft)	Scenario 4 (10^3 ac-ft)
Sacramento Basin							
Oroville	480	138	100	148	74	148	58
New Bullards Bar	170	120	73	120	59	131	55
Folsom	451	142	85	211	133	178	127
San Joaquin Basin							
Don Pedro	340	124	61	160	109	124	100
McClure / New Exch	350	98	64	92	60	49	45
Millerton / Friant	171	121	120	322	247	250	240

Table 1 represents the additional flood storage space (Additional CU Pool) in the reservoirs and the new yield generated from modeling the four scenarios. For the full-sized recharge basin scenarios (Scenarios 1&3), conjunctive use operations that focused on flood protection were able to secure between 98,000 acre-feet and 142,000 acre-feet of additional guaranteed flood protection space. When recharge basin sizes were reduced by half (Scenarios 2 & 4), conjunctive use pool sizes decreased up to 50% compared to the full-basin scenarios. This decrease was due to decreased storage capacity and ability to extract stored water represented by the smaller project area. Hence, the volume of new yield is more sensitive to recharge basin size than conveyance capacity.

Cost estimates to implement these conjunctive use operations range from $69 million to $300 million per sub-basin when considering land purchase, conveyance structure construction, extraction facility construction and well field operation and maintenance costs. HEC's findings include:

- New Exchequer and Friant Dams have the potential to provide the largest amount of new yield for the least cost.
- New Exchequer, New Bullards Bar and Friant Dams appear to provide the largest percentage increase in flood storage space for the least cost.
- Conjunctive use operation at Folsom and the three San Joaquin reservoirs provide the most significant flood protection as seen by the reduction in peak flows.

Because of the significant volume of reservoir storage space that could be made available, HEC determined that conjunctive use for flood protection merits further study. A strict management arrangement represents the simplest but costliest type of conjunctive use operations scheme, one that requires an active involvement by the Corps. An alternative to strict management would focus on contractual arrangements, which would allow for more local control but would require balancing flood control with new yield and habitat management goals.

The current system of surface water and groundwater laws establishes groundwater management and conjunctive use as highly decentralized and locality-specific. Any type of conjunctive use project will require basin-specific collaborative approaches that link reservoir water providers, landowners and end-users in a division of benefits. The projects should be sited as close as possible to surface water reservoirs and end water users and encourage participation from surface and groundwater users who reside within the affected floodplains.

COMPREHENISVE STUDY INFORMATION PAPER:

UPPER SACRAMENTO RIVER
HEC-RAS HYDRAULIC MODELING

This document outlines the work conducted for the Sacramento and San Joaquin River Basins Comprehensive Study to develop a hydraulic model of the upper Sacramento River. The purpose of this model was to establish existing hydraulic conditions and develop floodplain inundation areas. The California State Department of Water Resources, Division of Planning and Local Assistance, Northern District, developed a HEC-RAS hydraulic model extending from Woodson Bridge to Keswick Dam. This model was used to develop base (existing) condition water surface profiles and floodplain inundation maps along the upper Sacramento River. This document summarizes model development and analysis, topographic and hydrographic data, and base condition results.

HYDRAULIC ANALYSIS METHODOLOGY

Modeling Approach

The modeling approach for the upper Sacramento River reflects the availability of topographic data and study budgetary and schedule constraints. HEC-RAS was used due to its wide spread use and acceptance for calculating water surface profiles in natural channel systems. HEC-RAS has a graphical user interface that facilitates model development, troubleshooting, and visualization of results. Construction of the UNET models in the Sacramento River Basin involved developing intermediate HEC-RAS models, therefore this modeling approach also allows the flexibility to develop an upper Sacramento River UNET model in the future, should it be required.

Existing condition HEC-RAS modeling results were used to develop water surface profiles and floodplain inundation maps.

Floods Studied

The hydrology used with the upper Sacramento River HEC-RAS model was generated by the Comprehensive Study. Peak flows were derived from four storm centerings (Ord Ferry, Shasta, Sacramento, and Stony Creek) for three flood events (2%, 1%, and 0.5% probability of occurring in any year).

Description of Hydraulic Model

The purpose for developing the upper Sacramento River HEC-RAS model is to provide a tool for the Comprehensive Study to use in understanding and representing channel hydraulics along the upper Sacramento River. This reach of the Sacramento River was developed using a different hydraulic modeling technique than other areas in the Sacramento

Basin. The characteristics of the upper Sacramento River differ from lower reaches of the system, making this area somewhat separable from other Comprehensive Study hydraulic modeling efforts. In addition, topographic data collection along the upper Sacramento River was not completed until 2001, well after model development elsewhere in the system was underway.

Procedures and Process - In general, model construction consisted of collecting and processing topographic data, developing cross sectional geometry using the topographic and bathymetric data, and constructing the HEC-RAS model. Topographic data were collected for portions of the upper Sacramento River where current topography was not available. The survey data was processed electronically into digital surfaces, which were used to extract cross sections and delineate floodplains. HEC-RAS 3.0 was used in combination with AutoCAD and BOSS RMS (a-computer aided engineering application that provides an interface between AutoCAD and HEC-RAS) to produce water surface profiles and floodplain inundation mapping. Digital orthophotos obtained from the USGS were used as base maps for displaying the inundation areas.

Basic Assumptions and Limitations –The following are the basic capabilities, assumptions, and limitations inherent with the upper Sacramento River HEC-RAS model:

- The topography used in the overbank areas was derived from USGS 10-meter digital elevation models (30-meter for the Redding area). The detail of the model is dependent on the detail of the overbank topography.
- Cross section spacing in the HEC-RAS model varies from a few hundred feet to over one mile. Localized projects may require more detailed hydraulic models.
- Although HEC-RAS Version 3.0 is capable of performing unsteady flow analyses, the modeling performed for this study simulates a one-dimensional, steady flow regime. Hydraulic simulations were made using instantaneous peak flows only. This limits the volume-tracking capabilities of the model, as required for analyzing storage scenarios.
- Unlike UNET, no levee failures are assumed in the HEC-RAS model; flow stays in-channel until the top of levee or bank elevation is exceeded. HEC-RAS can track overbank flow, but does not consider geotechnical conditions.
- HEC-RAS performs a fixed-bed analysis (i.e. it does not account for bed movement, scour, or sediment deposition).
- Lower flow events (50%, 10%, and 4% flood hydrology) were not simulated as part of the initial modeling work. However, hydrologic flow data for other events is available and can be included in future studies.

HYDRAULIC ANALYSIS

Study Area and Model Extent

The model extends from Woodson Bridge near Vina to Keswick Dam above Redding. The model covers approximately 82 miles of the Sacramento River in Shasta and Tehama counties. Cross sections extend into overbank areas, generally meeting with high ground or natural terrace formations. Streams tributary to the Sacramento River were not included in the HEC-RAS hydraulic model, but the influence of these streams (Clear Creek, Cow Creek, Cottonwood Creek, Battle Creek, Elder Creek, Mill Creek, and Thomes Creek) were reflected in the hydrology.

Base Data

***Topographic and Hydrographic Data* -** Channel geometry data was developed from bathymetric surveys, performed for the entire study reach in 1999 and 2001. The 1999 data set includes the area from just downstream of Woodson Bridge to about 5 miles upstream from the bridge (part of the Sacramento River and Deer Creek Mapping Project). The 2001 data set includes the remainder of the reach upstream to Keswick Dam. A triangular irregular network (TIN) surface was developed from the bathymetric surveys, from which contours were generated at half-foot intervals. All raw bathymetric data was graphically reviewed, and edited if necessary.

Overbank geometry data was developed from U.S. Geological Survey (USGS) Digital Elevation Models (DEM's). Contours were generated at 5-foot intervals. The Sacramento River and Deer Creek Mapping Project contour data was used for all ground geometry data in that area of the study. Contours intervals were 2-foot in-channel and 5-foot in the overbank areas.

***Structures Affecting Flow* -** Bridges along the study reach were included in the HEC-RAS simulation. Bridge geometry and cross-sections were obtained from existing FEMA Flood Insurance Studies (FIS) and as-built bridge plans. For the City of Tehama, bridge cross-sections from the City of Tehama 205 Feasibility Study were used.

Model Input and Assumptions

***Channel Conditions* -** Manning's n values were set at 0.06 for overbank areas and 0.035 for the channel. Adjustments to these values were made, as necessary, based on field observations, engineering judgment, aerial photos, and channel geometry. Existing FEMA FIS models were referenced to obtain the appropriate range of roughness values used in the HEC-RAS model.

***Flow Data* -** The flows used with the upper Sacramento River HEC-RAS model were generated from Comprehensive Study hydrology. Peak flows were derived from four storm centerings (Ord Ferry, Shasta, Sacramento, and Stony Creek) for three flood events (2%, 1%, and 0.5%). The Stony Creek storm centering is the dominant storm event for the majority of the study reach. Instantaneous peak flows were developed at various locations: Woodson Bridge, Deer Creek confluence, Thomes Creek confluence, Mill Creek confluence, Elder Creek confluence, Bend Bridge, Battle Creek confluence, Cottonwood Creek confluence, Cow Creek confluence, Clear Creek confluence, and Keswick Dam. The event flows at these locations are included in Tables 1 through 3 for the 2%, 1%, and 0.5% flood events. The flows for the Battle Creek confluence were not used. HEC-RAS requires one-dimensional flow hydraulics.

TABLE 1
2% FLOOD EVENT FLOWS

Location Along Sacramento River	*Ord Ferry Centering*	*Sacramento Centering*	*Shasta Centering*	*Stony Centering*
Keswick	73,700	68,630	73,953	68,929
Clear Cr. Confluence	77,587	72,453	77,345	73,943
Cow Cr. Confluence	83,669	83,970	85,613	88,731
Cottonwood Cr. Confluence	137,447	131,131	117,989	164,863
Battle Cr. Confluence	158,499	150,316	135,641	186,760
Bend Bridge	154,222	146,266	131,992	181,688
Elder Cr. Confluence	156,140	150,439	135,189	186,703
Mill Cr. Confluence	168,494	164,319	150,435	201,545
Thomes Cr. Confluence	191,924	196,389	176,010	243,946
Deer Cr. Confluence	207,760	214,254	195,766	263,053
Vina Bridge	207,760	214,254	195,766	263,053

Note: The maximum instantaneous peak flow for each location is highlighted.

TABLE 2
1% FLOOD EVENT FLOWS

Location Along Sacramento River	*Ord Ferry Centering*	*Sacramento Centering*	*Shasta Centering*	*Stony Centering*
Keswick	78,745	73,953	78,859	73,953
Clear Cr. Confluence	84,615	78,488	85,134	80,232
Cow Cr. Confluence	101,097	89,772	106,219	100,142
Cottonwood Cr. Confluence	162,547	157,568	144,560	191,246
Battle Cr. Confluence	187,343	180,691	165,862	217,189
Bend Bridge	182,253	175,787	161,373	211,299
Elder Cr. Confluence	184,919	180,447	165,394	217,145
Mill Cr. Confluence	200,176	197,041	184,023	235,286
Thomes Cr. Confluence	231,016	236,662	217,940	288,057
Deer Cr. Confluence	250,533	257,947	241,794	311,296
Vina Bridge	250,533	257,947	241,794	311,296

Note: The maximum instantaneous peak flow for each location is highlighted.

TABLE 3
0.5% FLOOD EVENT FLOWS

Location Along Sacramento River	*Ord Ferry Centering*	*Sacramento Centering*	*Shasta Centering*	*Stony Centering*
Keswick	126,272	79,195	140,398	79,127
Clear Cr. Confluence	138,776	88,394	151,466	92,211
Cow Cr. Confluence	164,148	120,519	171,060	129,724
Cottonwood Cr. Confluence	228,900	183,383	224,976	216,168
Battle Cr. Confluence	241,160	210,422	235,786	246,316
Bend Bridge	234,364	204,692	229,248	239,575
Elder Cr. Confluence	229,774	210,089	225,905	246,183
Mill Cr. Confluence	236,889	229,875	234,375	267,861
Thomes Cr. Confluence	271,561	279,126	261,570	332,311
Deer Cr. Confluence	294,984	304,334	289,850	359,912
Vina Bridge	294,984	304,334	289,850	359,912

Note: The maximum instantaneous peak flow for each location is highlighted.

Boundary Conditions – Downstream boundary conditions for the HEC-RAS model were set as known water surface elevations. A separate water surface elevation was assigned for each storm event modeled, as shown in Table 4. Water surface elevations corresponding to the instantaneous peak flows were derived from a rating curve that was generated by UNET at river mile 214.0 (the upper end of the UNET model).

TABLE 4
DOWNSTREAM BOUNDARY CONDITIONS

Flood Event (probability)	Flow (cfs)	Water Surface Elevation (NGVD 29, ft)
2%	263,100	189.0
1%	311,500	190.8
0.5%	360,000	192.1

Model Verification

The 1983 storm event, a well-documented and major flood event in the upper Sacramento River, was run in the HEC-RAS model. These results were examined to assess initial model performance. A detailed calibration was not performed, but comparison of 1983 peak instantaneous stream gage data showed a close comparison with simulated model results. The comparison was made using 1983 gage data for the Sacramento River at Vina, Tehama, Red Bluff, and near Bend. A subsequent analysis found that the model was not highly sensitive to changes in channel roughness (Manning's n value), providing confidence in the channel roughness values used.

Baseline / Existing Condition Results

Baseline modeling results were published in February 2002 in a package titled *Upper Sacramento River Inundation Maps and Water Surface Profiles*. The results include water surface profiles for the 2%, 1%, and 0.5% flood events for the study reach, and floodplain inundation areas for these events were overlain on digital orthophotos.

CONCLUSIONS

The Upper Sacramento River HEC-RAS model is a useful regional planning tool for flood damage reduction and ecosystem restoration studies. The model represents one integral element of the suite of technical tools developed by the Comprehensive Study to gain a better understanding of existing conditions in the rivers and floodplains of the Sacramento and San Joaquin River basins.

Like other technical tools developed by the Comprehensive Study, the model is suitable for watershed-scale feasibility analyses. It is anticipated that this model would need to be improved before use as a local planning tool or on detailed studies. The upper Sacramento River HEC-RAS model is a ‘work in progress,’ and will likely change over time as more detailed data is collected and regional studies are performed. Additional work to build on the HEC-RAS model would include improving the detail of overbank geometry, collection of high water marks for the study reach, and detailed model calibration.

COMPREHENSIVE STUDY INFORMATION PAPER:

PRELIMINARY SIMULATION OF FLOOD CONDITIONS IN THE SACRAMENTO - SAN JOAQUIN DELTA

The Sacramento - San Joaquin Delta is a very complex hydraulic system influenced by tides, multiple tributary inflows, the timing of flood peaks, water supply pumping, and many other factors. Because changes to the Sacramento and San Joaquin River flood management systems could affect conditions in the Delta, a method was needed to evaluate the Delta during flood events and estimate any potential impacts. The Department of Water Resource's Delta Simulation Model II (DSM2) was adapted by the Comprehensive Study to evaluate existing hydrodynamic conditions in the Delta and perform preliminary evaluations of the effects of potential projects on flood flows and stages in the Delta.

DELTA SIMULATION MODEL

DSM2 was originally designed to evaluate water quality within the Delta under low-flow conditions, but was re-calibrated by the study to simulate floods. Modifications included additional definition of channel cross-sectional geometry and re-calibration using the 1997 flood event. The model was also truncated such that DSM2 flow input locations coincide with the downstream limits of the Sacramento and San Joaquin River UNET models, facilitating handoff of data between the two models.

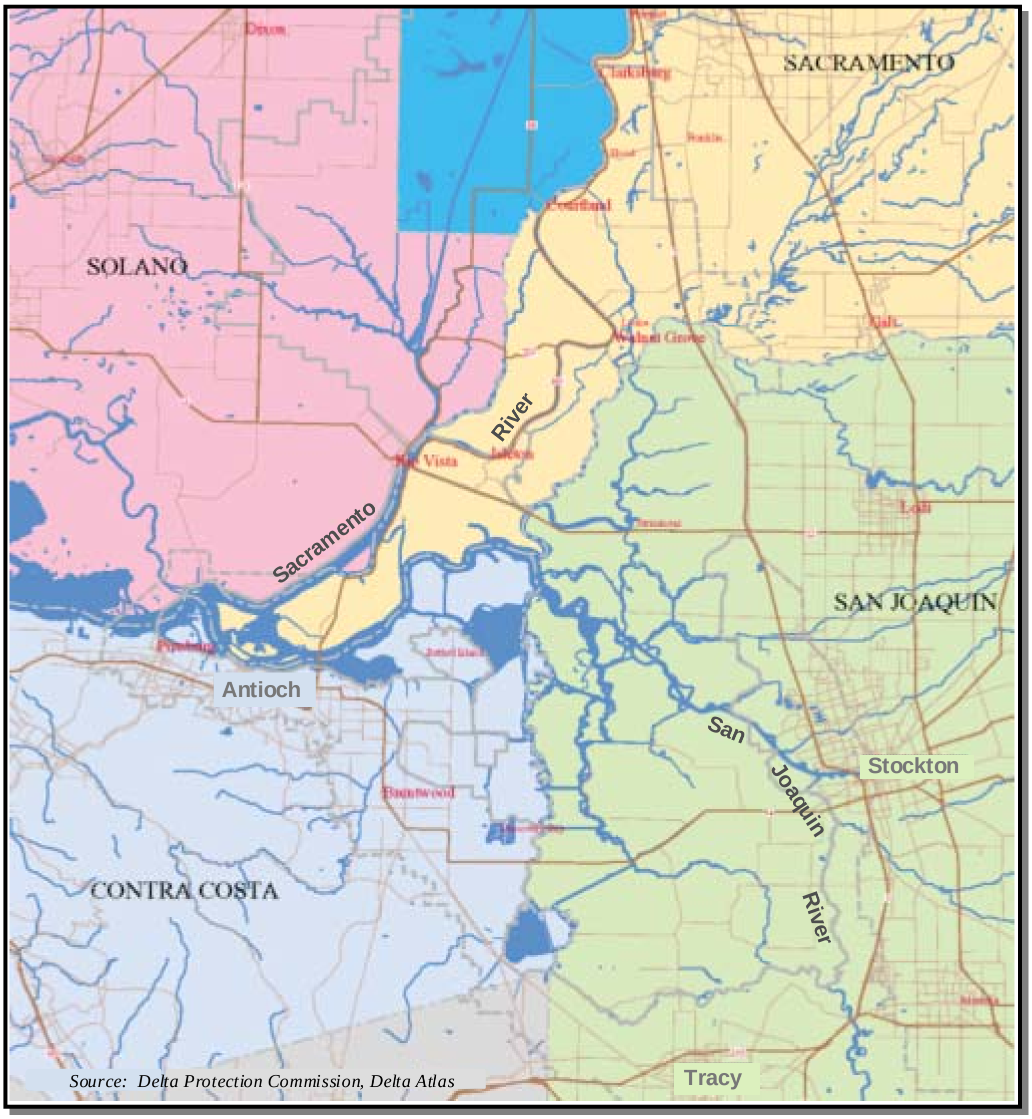
Channel geometry is reflected in DSM2 as cross sections, spaced at varying intervals. The model is not capable of simulating levee failure and does not take into account the extended high stages that often occur in the Delta and can affect levee stability. DSM2 input includes inflows provided by the UNET models, flood flows from other Delta tributaries (such as the Mokelumne and Calaveras rivers), and stage hydrographs reflecting downstream tide conditions near Martinez. Output from the DSM2 model includes stage (water surface elevation), flow, and storage volume data. The model supports evaluation of existing flood conditions in the Delta and can evaluate the effects of potential changes to Delta inflows or channels.

PRELIMINARY EVALUATIONS

DSM2 was used to gain a better understanding of existing hydrodynamic conditions in the Delta, evaluate potential channel modifications in the southern Delta, and perform a sensitivity analysis to determine how increased flood flows could affect stages and flows in the Delta. Although these evaluations were generalized, the results are informative and provide insight to how the Delta reacts during flood events.

Hydrodynamic Conditions in the Delta

DSM2 was used to simulate existing flood flow conditions within the Delta. Input to DSM2 consisted of simulated flows from the Sacramento River and San Joaquin River UNET models and flood event hydrology from Delta tributaries such as the Mokelumne and Calaveras rivers. The model was also used to evaluate how channel modifications in the South Delta could affect flood flows through the Delta. The results of the Delta hydrodynamics studies are documented in two reports covering the North Delta (lower Sacramento River to central Delta) and South Delta (San Joaquin River, from Stanislaus River to central Delta): *Existing Hydrodynamic Conditions in the Delta During Floods,* 2002



and *Lower San Joaquin River Assessment,* 2002, respectively. These information reports detail the modification and use of DSM2 to characterize flood conditions and evaluate potential project impacts in the Delta. The major findings of these studies are summarized below.

FIGURE 1 – THE SACRAMENTO - SAN JOAQUIN DELTA

Major factors that affect the flow of water trough the Delta include tributary inflows, tidal cycles, water project operations, and the physical configuration of the levee and waterway network. The Sacramento River flood peak usually arrives at the Delta before the San Joaquin flood peak during smaller flood events, but for larger events, the peaks can overlap due to the extended duration of Sacramento River flood flows. Studies indicate that the relative timing of peak flows arriving at the Delta may be more significant than the magnitude of the flows themselves, as a wide range of inflows have resulted in similar stages historically.

During large flood events, sustained peak flows from the Sacramento River Basin strongly influence stages in the north and central portions of the Delta. Sacramento River inflows create a barrier to flows entering from the South Delta. This hydraulic barrier suppresses flood flow in the San Joaquin River and Middle River, and results in water “backing up” in the South Delta area. This effect is particularly strong during high tide conditions.

As the hydraulic barrier develops near Georgiana Slough, Old River becomes the most important conveyance to drain south Delta inflows. Channel improvements in the South Delta, including widening Paradise Cut, dredging Old River, and widening Middle River would evacuate San Joaquin River flood flows more rapidly during more frequent flood events, but the effectiveness of these improvements is reduced in larger flood events, when inflow from the Sacramento River dominates Delta hydrodynamic conditions.

The affect of this hydraulic barrier was evident during the 1997 flood, when high tide conditions and high flow from the Sacramento River were the dominant factors controlling stage and flow in the Delta. Flows from the San Joaquin River were high, but less significant when compared with Sacramento River flood flows. Despite lower peak flows from the San Joaquin, most damages from flooding occurred in the south Delta because high stages from the Sacramento River prevented these flows from exiting the Delta. In addition, peak flows in the Cosumnes River were almost as high as those in the San Joaquin River, demonstrating the significant influence of the eastside tributaries.

Model simulations showed that the western Delta typically experiences increases in flood stage during low tide, but not during high tide periods. These results suggest that flood flows cannot overcome the influence of the ocean during high tide periods but effectively ‘fill in’ the void left by the receding tide, prolonging high stages. This also indicates that stages in the estuary downstream from Martinez are dominated by ocean tides and are less likely to be affected by changes in flood flows.

Flood damage reduction studies are often based on a level of protection defined by storm frequency or return frequency. However, this approach is not appropriate to define the occurrence of tidal cycles, which also have a significant effect on flood stage in the Delta. Variations in tides originate from gravitational forces and planetary movements, and have little relationship, if any, to the recurrence frequency of flood events.

Sensitivity to Changes in Flood Inflow

In addition to the existing condition evaluations described above, a series of sensitivity simulations were performed to learn how flood flows in the Delta would be affected if flood flows in the Sacramento or San Joaquin river were increased. Ten sensitivity simulations were performed; five based on 10-percent incremental increases in Sacramento River flows (with all other Delta inflow unchanged), and five based on similar percent increases in San Joaquin River flows. The 1- percent frequency event was used for the purpose of these evaluations. Flow hydrographs were modified by simple amplification of all flows based on the percentage increase. The timing of the flows was not modified because these evaluations were not intended to reflect an operated condition, but simply to evaluate the sensitivity of the Delta to change.

In general, these simulations found that increasing flood flows from the Sacramento River resulted in an increase in peak stage primarily in the central Delta region, with less significant stage increases to the west and the south. Increasing flows from the San Joaquin River resulted in an increase in peak stage primarily in the southern portion of the Delta, with less significant increases to central and western Delta areas. This exercise provides an indication of the areas that would be most sensitive to projects that change the timing or magnitude of flows entering the Delta. It should be noted that these results are very generalized and do not reflect changes in the entire Delta (as noted previously, the model was truncated to facilitate handoff of flows from UNET to DSM2), the effect of potential Delta levee failures, or changes in hydrograph shape that could result from increased flood volume. The results are informative, however, regarding the general hydrodynamic response in the Delta and the potential to convey higher flood flows through Delta channels. Table 1 provides a summary of peak flows corresponding to the existing condition and ten sensitivity simulations.

Table 2 provides a summary of changes in peak stage in the central and southern portions of Delta, as simulated in DSM2 for increases in Sacramento River flood flows for a 1-percent frequency event. Table 3 presents similar information for sensitivity simulations with increases in San Joaquin River flows, also for the 1-percent frequency event. To reflect the effect of relative differences in the timing of peak flows reaching the Delta from the Sacramento and San Joaquin rivers, several results are listed for each simulation: instantaneous peak, 5-day average peak, 10-day average peak, and 15-day average peak. For example, the 10-day average peak reflects the average peak stage experienced during the period starting five days before and ending five days after the instantaneous peak. The most notable increases in peak stage in the Sacramento River simulations (Table 2) are reflected in the 5-day average peaks, while the most notable increases in peak stage San Joaquin River simulations (Table 3) are reflected in the 10-day averages.

In general, increasing flood flows in the San Joaquin River resulted in stage increases in the southern Delta but had little affect on the central Delta. The greatest increases in stage were observed in the southern Delta for the simulation of a 50% increase in San Joaquin River flows. In contrast, increasing flows from the Sacramento River resulted in similar stage increases in both the central and southern Delta regions. This reflects the hydraulic barrier formed in the central Delta by the larger magnitude of flows entering from the Sacramento River, which limits flows from the south.

Limitations of Results

It should be noted that these results are preliminary in nature. They do not reflect changes in the entire Delta (the portion simulated in the UNET models is not included in the results), do not account for the effect of potential Delta levee failures, and do not account for potential changes in hydrograph shape that could result from increased volume. The evaluations were intended to provide a general understanding of hydrodynamic conditions in the Delta during floods, and identify how changes to the flood management system could affect the Delta.

TABLE 1
SUMMARY OF DELTA SENSITIVITY EVALUATION PEAK INFLOWS

Case		Total Sacramento Peak Inflow (1,000 cfs) [a]	Total San Joaquin Peak Inflow (1,000 cfs) [a]	Total of Other Peak Inflows (1,000 cfs) [a]
Existing Condition (1-percent flood)		626	27	97
Sacramento River Inflow	10% Increase	688	27	97
	20% Increase	750	27	97
	30% Increase	814	27	97
	40% Increase	876	27	97
	50% Increase	939	27	97
San Joaquin River Inflow	10% Increase	626	30	97
	20% Increase	626	33	97
	30% Increase	626	35	97
	40% Increase	626	38	97
	50% Increase	626	41	97

Notes:
a. Values represent the sum of multiple input locations, rounded to nearest 1,000 cfs. For example, the Sacramento River peak inflow includes northern tributary inflows such as the Sacramento River and Yolo Bypass. Similarly, Other Peak Inflows includes eastside Delta tributaries such as the Mokelumne and Calaveras rivers.

TABLE 2
SUMMARY OF CHANGES IN PEAK STAGE, 1-PERCENT FREQUENCY EVENT WITH INCREASES IN SACRAMENTO RIVER FLOW

Change in Sacramento River Flow	Peak Output Condition	Increase in Peak Stage (ft) Central Delta	South Delta
10 Percent Increase	Instantaneous	0.15	0.10
	5-Day Average	0.20	0.15
	10-Day Average	0.15	0.15
	15-Day Average	0.15	0.10
20 Percent Increase	Instantaneous	0.20	0.15
	5-Day Average	0.40	0.30
	10-Day Average	0.40	0.30
	15-Day Average	0.30	0.20
30 Percent Increase	Instantaneous	0.60	0.40
	5-Day Average	0.70	0.60
	10-Day Average	0.60	0.50
	15-Day Average	0.45	0.40
40 Percent Increase	Instantaneous	0.80	0.65
	5-Day Average	0.95	0.90
	10-Day Average	0.85	0.80
	15-Day Average	0.65	0.60

50 Percent Increase	Instantaneous	1.10	1.00
	5-Day Average	1.25	1.20
	10-Day Average	1.10	1.00
	15-Day Average	0.85	0.80

TABLE 3
SUMMARY OF CHANGES IN PEAK STAGE, 1-PERCENT FREQUENCY EVENT WITH INCREASES IN SAN JOAQUIN RIVER FLOW

Change in San Joaquin River Flow	Peak Output Condition	Increase in Peak Stage (ft)	
		Central Delta	South Delta
10 Percent Increase	Instantaneous	0.05	0.20
	5-Day Average	0.05	0.30
	10-Day Average	0.05	0.35
	15-Day Average	0.05	0.35
20 Percent Increase	Instantaneous	0.10	0.45
	5-Day Average	0.10	0.65
	10-Day Average	0.10	0.80
	15-Day Average	0.10	0.80
30 Percent Increase	Instantaneous	0.10	0.80
	5-Day Average	0.10	1.10
	10-Day Average	0.10	1.20
	15-Day Average	0.10	1.20
40 Percent Increase	Instantaneous	0.10	1.25
	5-Day Average	0.15	1.50
	10-Day Average	0.15	1.50
	15-Day Average	0.15	1.40
50 Percent Increase	Instantaneous	0.15	1.50
	5-Day Average	0.15	2.00
	10-Day Average	0.15	2.00
	15-Day Average	0.15	1.75

COMPREHENSIVE STUDY INFORMATION PAPER:

GLOBAL CLIMATE CHANGE

The purpose of this document is to describe how global climate change could affect the Sacramento and San Joaquin River Basins Comprehensive Study and future decisions regarding flood management and environmental restoration in the floodways and floodplains of California's Central Valley. The federal government recognizes that global climate change is a serious environmental concern. Given the current state of scientific knowledge, continued emissions of 'greenhouse gasses,' greenhouse sinks, and other changes in the atmosphere must be viewed under NEPA as a reasonably foreseeable impact. Therefore, federal agencies must analyze the extent to which their proposed and ongoing actions and activities could influence such emissions and sinks. Such analyses should consider how federal actions could affect global climate change and, to the extent possible, how global climate changes could affect federal actions.

HISTORIC EVIDENCE

Scientists know that human activities are changing the composition of Earth's atmosphere. Scientific evidence indicates that there has been a global rise in average annual temperature of at least one degree Fahrenheit (°F) in the past one hundred years. This increase exceeds anything documented over the past thousand years. Warming has occurred in both the northern and southern hemispheres, and over the oceans. Confirmation of 20th-century global warming is further substantiated by melting glaciers, decreased snow cover in the northern hemisphere, and even warming below ground

Scientists agree that greenhouse gases trap heat in the Earth's atmosphere and tend to warm the planet. By increasing the levels of greenhouse gases in the atmosphere, human activities are strengthening Earth's natural greenhouse effect. Many scientists also agree that the recent atmospheric buildup of carbon dioxide and other greenhouse gases is largely the result of human activities. Increasing levels of greenhouse gases in the atmosphere, such as carbon dioxide (CO_2), have also been well documented since pre-industrial times. Evidence from ice cores and air samples all over the globe show a dramatic increase on carbon dioxide and anthropogenic gasses such as methane. The role of methane is quite significant in the apparent increase in temperature. The key greenhouse gases emitted by human activities remain in the atmosphere for long periods, from decades to centuries.

Sea level changes also are directly related to extremes in climate change. Historically, changes in sea level have been irregular and primarily a result of thermal expansion of the water itself, rather than melting of polar ice. Sea levels were, on average, from 2 to 6 meters higher than present levels during the last interglacial period 125,000 years ago, and about 120 meters below present levels during the last ice age 20,000 years ago. Sea levels have increased by 10-25 cm over the last century. For example, the mean sea level at the Golden Gate Bridge has risen approximately 6.25 inches over the past 100 years (CALFED Phase II Report, 2000). Given this fluctuation, it is likely that the Sacramento-San Joaquin Delta as we know it - with sea level near its current level - has existed for only a short amount of geologic time.

Based on analysis of ice cores and tree ring data, there was a long term cooling trend over the past thousand years up until about 150 years ago, when the industrial revolution began. After then, there has been a dramatic increase in temperature all over the world. This is demonstrated by substantial glacial retreat, a decrease in snow cover in high latitude regions, and a significant increase in the annual freeze-free period. Locally, the average temperature in Fresno, California, has increased from 61.9°F (1899-1928 average) to 63.3°F (1966-1995 average) over the last century. Precipitation has decreased by up to 20% in many parts of the state, and California's climate may change even more over the next century. Continued increases in temperature and rainfall would mean more rain and less snow at higher elevations, reducing the winter snow-pack that sustains many of California's rivers through spring and into summer.

CURRENT UNDERSTANDING OF GLOBAL CLIMATE CHANGE

It is not easy to determine the extent to which the human-induced accumulation of greenhouse gases since pre-industrial times is responsible for the global warming trend. This is because many other factors, both natural and human, affect our planet's temperature. Scientific understanding of these other factors – most notably natural climatic variations, changes in the sun's energy, and the cooling effects of pollutant aerosols – remains incomplete. Nevertheless, the Environmental Protection Agency (EPA) sponsored Intergovernmental Panel on Climate Change (IPCC). The IPCC, which represents more than 2,000 of the world's leading climate scientists, concluded, "the balance of evidence suggests that there is a discernible human influence on global climate," and that the observed warming trend is "unlikely to be entirely natural in origin." In the most recent *Third Assessment Report* (2001), IPCC wrote "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."

In short, scientists think rising levels of greenhouse gases in the atmosphere are contributing to global warming; but to what extent is difficult to determine at the present time. As atmospheric levels of greenhouse gases continue to rise, scientists estimate average global temperatures will continue to rise as a result. By how much and how fast remain uncertain. The IPCC projects further global warming of 2.2-10°F (1.4-5.8°C) by the year 2100. This range results from uncertainties in greenhouse gas emissions, the possible cooling effects of atmospheric particles such as sulfates, and the climate's response to changes in the atmosphere. The IPCC states that even the low end of this warming projection "would probably be greater than any seen in the last 10,000 years, but the actual annual to decadal changes would include considerable natural variability."

Uncertainties

Our current understanding of the potential impacts of climate change is limited by critical scientific uncertainties:

- How much more warming will occur?
- How fast will this warming occur?

- What are the potential adverse and beneficial effects?
- Where will the effects be most pronounced?

These uncertainties will be with us for some time, perhaps decades. We know that global warming poses real risks, but the exact nature of these risks remains uncertain. Ultimately, this is why scientists have to use their best judgment, guided by current scientific capabilities, to determine what the most appropriate responses to global warming should be.

One obstacle relates to the inadequacy of regional-scale models and the inability to accurately project spatial variability in natural and human systems. For example, scientists are more confident about global projections (global temperature and precipitation change, average sea level rise) and less confident about projections for smaller areas (local temperature and precipitation changes, altered weather patterns, soil moisture changes). This is largely because the computer models used to forecast climate change are extremely complicated and data-intensive, making them ill-equipped to simulate highly localized conditions. This uncertainty is compounded further by the uncertainties inherent in ecological, economic, and social models, which further limit our ability to identify the full extent of climate change impacts or potential adaptation measures. Given these uncertainties, particularly the inability to forecast futures, conclusions about regional impacts are not yet reliable and are limited to the potential *sensitivity* and *vulnerability* of physical, biological, and socioeconomic systems to climate change and variability.

Some of the greatest uncertainties related to global climate change are associated with events that pose the greatest risk to public safety. IPCC cautions, "Complex systems, such as the climate system, can respond in non-linear ways and produce surprises." There is the possibility that a warmer world could lead to more frequent and intense storms, including hurricanes. Preliminary evidence suggests that, once hurricanes do form, they will be stronger if the oceans are warmer due to global warming. However, the jury is still out whether or not hurricanes and other extreme weather events will become more frequent.

Predicted Trends and Potential Impacts

Based on the predictions of the various global climate or circulation models, it is anticipated that there will be a rise in average annual temperature of between two-and-a-half and ten °F over the next thousand years, depending on the model used, with approximately half of the increase likely to occur during the next fifty years. Most modeling also suggests an increase in average annual precipitation around the world because of the raise in temperature. This would induce considerable melting of the polar ice cap and glacial ice, resulting in additional increases in sea level of between one to two feet on the west coast.

Climate model projections also suggest increased runoff in winter and early spring but reduced flows during summer in regions in which hydrology is dominated by snowmelt. Glaciers are expected to retreat, and their contributions to summer flows will decline as peak flows shift to winter or early spring. In mountainous regions, particularly at mid-elevations, warming leads to a long-term reduction in peak snow-water equivalent because the snow pack builds later and melts sooner. River and reservoir systems that are fed by snowmelt or glaciers and typically supply spring and summer flow during critical periods of high agricultural and municipal demand and low precipitation, may tend to release their water earlier in the year, which would reduce supplies during summer droughts. Water supplies and water quality, irrigation, hydroelectric generation, tourism, and fish habitat, as well as the viability of the livestock industry, may be negatively impacted by changes in seasonal water delivery. The Great Plains of the United States and prairie regions of Canada and California are particularly vulnerable.

Altered precipitation and temperature regimes may cause lower lake levels, especially in midcontinental regions, and affect lake and wetland function in terms of flood protection, water filtration, carbon storage, and waterfowl/ wildlife habitat. However, the response of an affected wetland is uncertain; it might include migration along river edges or the slope of a receding lake, or altered vegetation species composition.

Sea level rise could lead to flooding of low-lying property, loss of coastal wetlands, erosion of beaches, saltwater contamination of drinking water, and decreased longevity of low-lying roads, causeways, and bridges. In addition, sea level rise could increase the vulnerability of coastal areas to storms and associated flooding.

POTENTIAL REGIONAL IMPACTS

Within the North American region (defined by EPA as the portion of continental North America south of the Arctic Circle and north of the U.S.-Mexico border), vulnerability to climate change varies significantly from subregion to subregion. Recognition of this variability or subregional "texture" is important in understanding the potential effects of climate change on North America and in formulating viable response strategies. The varied characteristics of the subregions of North America suggest that neither the impacts of climate change nor the response options will be uniform. In fact, simply considering the relative climate sensitivity of different areas or systems within a particular subregion (i.e., climate-sensitive, climate-insensitive, or climate-limited) would suggest differentiated impacts.

Within most natural and human systems in North America, the current climate - including its variability - is frequently a limiting factor. For example, climate affects natural ecosystems, agricultural efficiency, public health, and the economy. Climate, however, is only one of many factors that determine the overall condition of these systems. For example, projected population growth in North America and associated changes in land use and air and water quality will continue to put pressure on natural ecosystems (e.g., rangelands, wetlands, and coastal ecosystems). Projected changes in climate should be seen as an additional factor that can influence the health and existence of natural and human systems. In some cases, changes in climate will provide adaptive opportunities for habitat or could alleviate the pressure of multiple stresses; in other cases, climate change could hasten or broaden negative impacts, leading to reduced ecosystem function or elimination of ecosystems (EPA 2001). Climate change could have similarly uncertain affects on the agricultural economy, with some land becoming more productive while other lands become less productive.

Regionally, the change in climate will likely result in a shift in west coast weather patterns, characterized by warmer storms that occur later in the season. It is also quite likely that the typical storm pattern will shift north or south from its current alignment. The amount of precipitation on extreme wet days most likely would increase, especially in the winter and fall, and there could be a decrease in the number of long dry spells and an increase in the number of long wet spells.

Projections given by the IPCC and results from the United Kingdom's Hadley Centre climate model (HadCM2), indicate that by 2100 temperatures in California could increase by about 5°F (with a range of 2-9°F) in the winter and summer, and slightly less in the spring and fall. Appreciable increases in precipitation are also projected in California: 20-30% in spring and fall, with somewhat larger increases in winter. Little change is projected to occur during the summer months.

Water Resources Impacts

Currently, more than half of the precipitation that falls in California above 5,000 feet is in the form of snow. However, warmer storms would deliver rain at higher elevations, resulting in less water being stored in the snow pack. These changes would affect the amount and timing of runoff, and have far-reaching affects on flood control and water supply. Winter runoff most likely would increase, while spring and summer runoff would decrease. This shift could be problematic because the existing reservoirs rely on late-season precipitation and snowmelt and are not large enough to store the increased winter flows for release later in the summer. Under current projections, there would be a significant decrease in the amount of moisture in the snow pack and the amount of spring run-off in the Sacramento River Basin. Unless the storm track shifts to the south, the San Joaquin River Basin would not be affected as significantly because it normally does not receive as much precipitation and would still receive a considerable quantity as snowfall in the southern Sierra Nevada.

Water resources in California are also affected by changes in temperature, humidity, wind, and sunshine. Because evaporation is likely to increase with warmer climate, it could result in lower river flows and lower lake levels, particularly in the summer. If streamflow and lake levels decrease, groundwater recharge could also be affected. In addition to the affects on reservoir operations, more intense precipitation could increase the frequency of flooding.

Impacts to Coastal and Delta Regions

Along much of California's coast, sea level is already is rising by 3-8 inches per century (3 inches at Los Angeles, 5 inches at San Francisco, and 8 inches at San Diego), and it is likely to rise by another 13-19 inches by 2100. Sand has been imported to beaches stretching from Santa Barbara to San Diego, and these beaches will undoubtedly require future sand replenishment or protection with structures if threatened by further sea level rise. The cumulative costs for sand replenishment to protect California's coastline from a 20-inch sea level rise through 2100 could be between $174 million and $3.5 billion.

San Francisco Bay contains the most extensive salt marshes on the West Coast, most of which have been modified dramatically by dredging and filling activities. An increase in sea level between 1 and 3 feet may move the existing salt marshes in the bay inland to nearby lowlands and freshwater marshes, but development will probably limit the extent to which these marshes can "migrate" to new areas. A 1 to 3 feet rise in sea level would also result in the erosion or submergence of Delta wetlands, and many Delta islands would be submerged. Increased winter flows could also increase the risk of flooding in the Delta. The fragile environment of Delta islands could be at risk from increased flooding and the upstream movement of saltwater from the bay.

Environmental Impacts

Global climate change poses risks to human health and to terrestrial and aquatic ecosystems in the region. Important economic resources such as agriculture, forestry, fisheries, and water resources also may be affected. Warmer temperatures, more severe droughts and floods, and sea level rise could have a wide range of impacts in the state. Climatologic stresses on California's ecological resources would be exacerbated by other influences such as population growth, land-use changes, and pollution. Specific ecological responses to climate change cannot be predicted, because new combinations of native and non-native species will interact in novel situations. Such novel interactions may compromise the reliability with which ecosystem goods and services are provided by aquatic and wetland ecosystems.

Similar temperature changes have occurred in the past, but the previous changes took place over centuries or millennia instead of decades. The ability of some plants and animals to migrate and adapt to such rapid changes appears to be much slower than the predicted rate of climate change. Some concerns related to human health and the ecosystem are summarized below:

- Seasonal shifts in stream runoff will have significant negative effects on many aquatic ecosystems. Streams, rivers, wetlands, and lakes in the western mountains are most likely to be affected, because these systems are strongly influenced by spring snowmelt and warming will cause runoff to occur earlier in winter months. Changes in precipitation and runoff modify the amount and quality of habitat for aquatic organisms, and thus, they indirectly influence ecosystem productivity and diversity.
- Aquatic and wetland ecosystems are particularly vulnerable to climate change. The metabolic rates of organisms and the overall productivity of ecosystems are directly regulated by temperature. Increases in water temperature will cause a shift in the thermal suitability of aquatic habitats for fish and other resident species, affecting the distribution and movement of plants and animals. Fish in lowland streams and rivers that lack northward connections to cooler waters, and species that require cool water (e.g., trout and salmon) are likely to be the most severely affected. At the same time, other species may expand their ranges.
- Increased water temperatures and seasonally reduced streamflows will also alter many ecosystem processes with potential direct societal costs. For example, warmer waters in combination with high nutrient runoff are likely to increase the frequency and extent of algal blooms, thereby reducing water quality and posing potential health problems. Algal blooms and other warm-water pant life can also affect the operation and efficiency of water diversion pumps, fish screens, and agricultural conveyance systems.
- Coastal wetlands are particularly vulnerable to sea-level rise associated with increasing global temperatures. Inundation of coastal wetlands by rising sea levels threatens wetland plants. For many of these systems to persist, a continued input of suspended sediment from inflowing streams and rivers is required to allow for soil accretion.

AFFECTS ON THE COMPREHENSIVE STUDY

Global climate change raises a wide range of concerns that should be addressed by national, State and local water managers and planners. As discussed previously, the anticipated impacts of global and regional warming include more winter runoff and less snow pack, increases in sea level, changing storm patterns (timing, frequency, duration, intensity), and shifts in suitable aquatic and terrestrial habitats. Considering California's heavy dependence on reservoirs and snow pack for water supply and flood management, climate change makes this state especially vulnerable to hydrologic changes. Therefore, the impacts and uncertainties of climate change need to be evaluated in future studies to ensure that Central Valley water systems can continue to provide adequate flood protection, water supply, ecosystem functions, and overall system flexibility. For this reason, consideration for global climate change is included in the Comprehensive Plan's guiding principles. CALFED has also acknowledged the importance of climate change and has collected valuable scientific information and resources pertinent to the Comprehensive Study planning area. Future projects can address climatic uncertainties in numerous ways:

- A systematic review and evaluation of California's existing water control system - including engineering designs, operating rules, contingency plans and water allocation policies - under a wider range of climate conditions
- Evaluating the relative costs and benefits of structural and non-structural management options in the context of changing climate, to identify actions that are both effective and flexible under different hydrologic conditions
- Determining the impacts of storm frequency and severity on water quality, levee stability, ecosystems, and flood flow dynamics
- Identifying gaps and uncertainties in available information for further research
- Coordination and cooperation between water agencies and leading scientific organizations to facilitate the exchange of information about climate change and its impacts on water resources.

Water supply reliability, environmental health, and even human safety all benefit from long-term strategic planning. Just as you would not design a city's water system without considering future population growth, future water control systems should not be designed without considering future hydrologic changes. Water management planning for future climatic and hydrologic conditions can significantly reduce system vulnerability and long-term costs. Ultimately, the manner in which humans adapt to a changing climate will probably have the greatest influence on the future of water resources and the ecosystem in the Sacramento and San Joaquin River Basins.

COMPREHENSIVE STUDY INFORMATION PAPER:

SUBSIDENCE IN THE CENTRAL VALLEY

The purpose of this document is to describe how land subsidence could influence the Sacramento and San Joaquin River Basins Comprehensive Study decision-making process and future decisions regarding the flood management system and ecosystem restoration in floodplains of the Central Valley. This document presents information and preliminary conclusions developed during the course of the Comprehensive Study that may be of use to future studies, but it does not represent a detailed study of subsidence or all of the factors that could influence subsidence in the Central Valley.

Land subsidence is a lowering in elevation, or “sinking”, of the land surface that can result from manmade actions or natural processes. The largest occurrence of land subsidence in the world induced by human activity is in the California Central Valley (Bertoldi et al, 1991). In the Comprehensive Study planning area, groundwater extraction in excess of recharge (groundwater overdraft) is the primary cause of subsidence. Significant subsidence can change the expression of fluvial geomorphic processes, which changes how stream channels react with the landscape. This can adversely affects the performance of flood control channels, levees, and water supply conveyance channels.

EXISTING CONDITIONS

Subsidence in the Central Valley develops most rapidly during periods of drought when groundwater pumping for irrigation and other purposes is high and less surface water is available for recharging aquifers. This effect is more pronounced in the arid San Joaquin Valley than in the Sacramento Valley, where more surface water is available for water supply and more precipitation recharges groundwater aquifers. Consequently, subsidence in the Sacramento River Basin tends to be localized and concentrated in areas that are not well served by surface water supplies. Subsidence is more extensive in the San Joaquin River Basin where there is a greater reliance on groundwater for irrigation, and soil conditions and the arid climate provide less groundwater recharge.

Subsidence in the Sacramento River basin has been observed most notable between Zamora and Knight’s Landing. In this area, subsidence rates were about 0.25 feet/year between 1973 and 1979 and only about 0.03 feet/year between 1979 and 1986. This demonstrates how subsidence due to groundwater extraction can change between drought years and wet years. These fluctuations are dependent upon weather patterns, which make it difficult to accurately predict future demand on groundwater and subsequent subsidence.

Planert and Williams (1995) reported that by 1977 about half of the San Joaquin Valley had subsided by at least one foot, with a total volume of subsidence of 17 million acre-feet. The most dramatic subsidence has occurred in area southwest of Mendota, which subsided almost thirty feet between the 1920’s and the late 1970’s. Generally, the rate of subsidence slowed in the 1970’s as surface water use increased dramatically following construction of water supply reservoirs and water delivery systems. Other studies providing information on subsidence effects are listed at the end of this document under References.

COMPREHENSIVE STUDY FOCUS

The portion of the Sacramento and San Joaquin River Basins flood management systems most significantly affected by subsidence is the southwestern part of the San Joaquin Valley, upstream of the San Joaquin – Merced River confluence.

In calibrating the complex, basin-wide computer models developed by the Comprehensive Study, it was necessary to incorporate accurate topographic information to predict the behavior of major flood events. The U.S. Geological Survey 30-meter Digital Elevation Model (DEM) data was used to describe floodplain geometry. This data was prepared in 1960 and needed to be adjusted for any subsidence that occurred between 1960 and the Comprehensive Study base year of 2000/2001. In general, the adjustment to "update" the 30-meter DEM data was made by comparing elevations from topographic data collected by the Corps of Engineers (Corps) in 1998 to elevations derived from the 1960 DEM data. **Figure 1** shows resulting contours of the estimated annual rates of subsidence. The total adjustment values applied to the 30-meter DEM data for the base year topography is equal to the annual rates shown in **Figure 1** multiplied by 40 years. It should be noted that the approach to adjust the DEM data is approximate and is probably more accurate along the watercourses (which were surveyed in 1998) compared to the floodplain areas farther away from the surveyed channels. However, given the available information, the approach did produce a reasonable floodplain surface on which the floodplain FLO-2D models were developed.

When the Corps conducted its survey of watercourses in the San Joaquin River basin in 1998, the vertical datum used in the survey was the National Geodetic Vertical Datum of 1929 (NGVD 29). This vertical control utilized benchmarks that are likely to have been affected by subsidence. Therefore, the Corps conducted a "Discovery Survey" in 2000 of the southern San Joaquin River basin. The main purpose of this survey was to extend the vertical control to outlining benchmarks, known to be free from subsidence, and to determine the adjustments necessary to modify the 1998 mapping so that it would more accurately represent true topographic conditions.

An unintended by-product of the Discovery Survey was the development of a sufficient amount of elevation data with which estimates could be made regarding the rates of subsidence over the past 3 to 70 years (depending on the specific location of interest). The estimated rates are illustrated on **Figure 2** and led to the following conclusions:

1) The overall areal extent of subsidence is somewhat larger than originally thought, extending further to the north and east, and

2) The rates of subsidence are somewhat less than those originally estimated before the Discovery Survey, with the exception of the area near the intersection of Highway 152 and the Eastside Bypass.

Comparing **Figures 1** and **2** shows two substantially different pictures of subsidence activity in this part of the San Joaquin Valley. This graphically demonstrates how two sets of subsidence data, which differ both spatially and temporally, may yield different interpretations. It also demonstrates that long-term predictions of future subsidence activity based upon past trends are tenuous, at best. This is due, in part, to fluctuations in groundwater pumping in response to changing climate conditions and water availability.

The difficulty of predicting future subsidence notwithstanding, **Figure 3** shows projected subsidence that could occur between now and 2060, based upon the subsidence rates displayed in **Figure 2**. The maximum subsidence shown in **Figure 3** is 17 +/- feet along the Eastside Bypass channel, approximately halfway between the connector channel and Ash Slough

Using the information developed by the Discovery Survey, the 1998 riverine topography has been adjusted to account for subsidence of survey benchmarks. However, new cross section geometry using this adjusted data has not yet been developed and incorporated into the San Joaquin River basin UNET or HECRAS models used by the Comprehensive Study to estimate the effects and benefits of future projects. It is assumed that the information presently in the models is adequate for determining the base-condition, as well as considering future conditions at a programmatic level of planning. This assumption is based on engineering judgment and by the fact that the maximum adjustment to the 1998 topography was 1.8 feet for the base-condition. Future studies should consider how prospective planning scenarios could be affected by subsidence and utilize the topographic information that best fits the study's needs.

IMPACTS OF SUBSIDENCE

Flood Management System Impacts

Subsidence adversely affects a flood management system by lowering the effective heights of levees and other protective features and/or changing the gradient (slope) of the stream channel. Increasing stream gradient (making channels steeper) tends to decrease channel meandering while increasing channel downcutting (bed erosion) that, in turn, can threaten levee integrity. Lowering stream gradients reduces channel capacity, increases sedimentation, and increases lateral channel migration, which can also threaten levee integrity.

Significant flood management impacts are expected at locations where subsidence exceeds two feet over the life of the project. The most significant impact of subsidence will be on channel gradients, which have a direct impact on channel capacity, flow velocities, and aggradation and degradation trends. It is important to note that since subsidence appears to be widespread in the San Joaquin Valley, at any location of interest along the channels, the distance between the channel invert and the top of levee will remain constant (assuming minimal aggradation or degradation), while the channel slope from upstream to downstream may be steepened or flattened. At locations where the subsidence is very pronounced (e.g., the location along the Eastside Bypass mentioned above), levees may no longer be able to contain the same flows because downstream water surface elevations (backwater) will remain relatively unchanged while the top of the levees may be up to 17+/- feet lower than is necessary to contain the flow. In all, it appears that approximately 240 miles of the San Joaquin River system may be impacted by subsidence over the next 50 years.

This interpretation is supported by recent work in the Eastside Bypass channel wherein a 5-mile reach of the levees was raised in 2000 so that the channel would continue to contain the design flows. This levee raising was required as a direct consequence of subsidence in the southern San

Joaquin River basin and was located in the vicinity of where 17+/- feet of subsidence is predicted to occur over the next 60 years, as shown in **Figure 3**.

Impacts to the Environment

Subsidence has the greatest potential to affect environmental conditions when differing rates of subsidence alter the gradient of a waterway. In instances where the stream gradient is increased, there will be higher stream velocities, increased erosion and channel downcutting (incision), diminished meander activity, and higher rates of drainage (decreasing wetlands). Conversely, where the stream gradient is lowered there will be lower stream velocities, less erosion, increased sediment deposition and shoaling, greater potential stream meandering over a larger area, and lower rates of drainage (increasing wetlands). Over time, areas with lowered stream gradients will likely experience sediment deposition that can degrade in-stream aquatic habitat.

Other Impacts

To date, subsidence has seriously impacted irrigation/water supply delivery systems such as the California aqueduct. In general, a pronounced low area is forming along the California Aqueduct, causing water to pool over several miles and reducing the overall efficiency of the aqueduct. Other canals such as the Delta-Mendota, Main, and Outside canals have also been affected by subsidence. It is also reasonable to expect that many of the drain systems located throughout the southwestern San Joaquin River basin may be impacted by subsidence, affecting their ability to remove and convey irrigation return water.

CONCLUSIONS

Given the results of the Discovery Survey and the shortcomings associated with analyses to predict future subsidence, it would be helpful to conduct additional research into the history of the benchmarks used in the study area. The period of record and the date of the last benchmark measurement is not always well documented. In these instances, a best estimate was used to determine the amount of time that has elapsed since the benchmark was last surveyed and, subsequently, the estimated subsidence.

Additionally, a program to monitor the elevation of a selected set of benchmarks located along the project reaches (i.e., forming a control network) would provide reliable data using the same benchmarks, instead of comparing data sets that may have different benchmarks. This work would conceivably require that a survey of the network be conducted periodically (e.g., every five years or so) and a good understanding would be obtained as to where and how much subsidence was occurring. Lofgen and Ireland (1973) promote two different methodologies for estimating future subsidence caused by groundwater extraction, both of which are complicated and costly. Alternatively, an approach using newer technology, such as Differential Synthetic Aperture Radar Interferometry, that does not require benchmarks could be used to monitor subsidence. In any event, some effort to more effectively predict future levels of subsidence should be undertaken for the existing flood control system and/or any future project given the significant impacts it could have on flood control and water delivery systems.

Comprehensive Study

Future flood damage reduction and ecosystem improvement projects should take into account land subsidence in their planning and design to compensate for potential future affects. Future subsidence will likely manifest itself as either increased flood damages due to reduced effectiveness of the flood management system, or increased operation and maintenance costs incurred to compensate for the subsidence effects.

The latest revised topography accurately reflecting present and predicted future subsidence should be used in future, more detailed planning studies to develop system-wide, regional or local projects. With this information, levees and other flow management structures can be appropriately designed and constructed such that improvements will realize all of their planned benefits, and ecosystem improvements efforts can account for changes in geomorphic processes.

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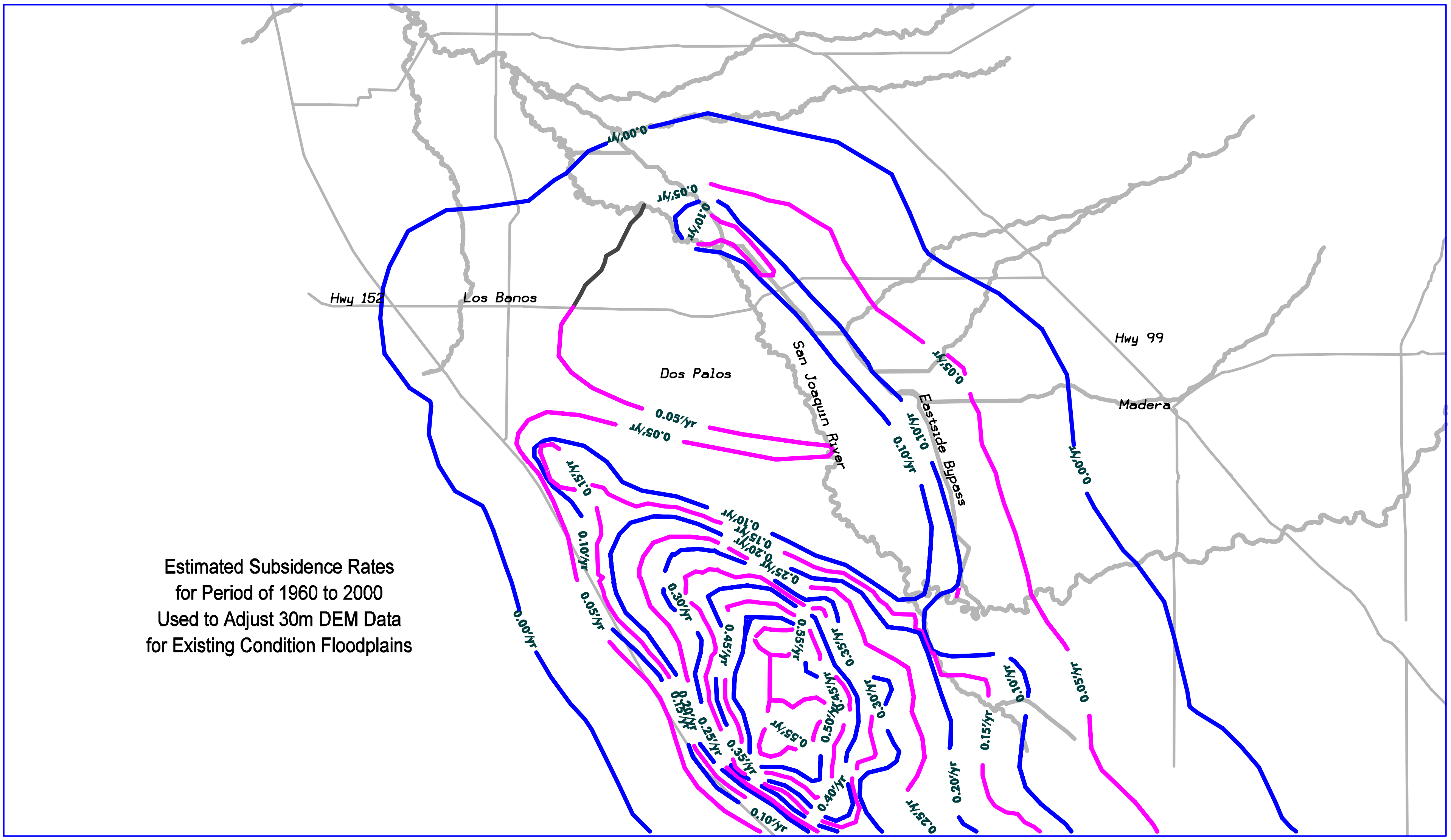

FIGURE 1- ESTIMATED SUBSIDENCE RATES USED TO ADJUST EXISTING CONDITION FLOODPLAINS

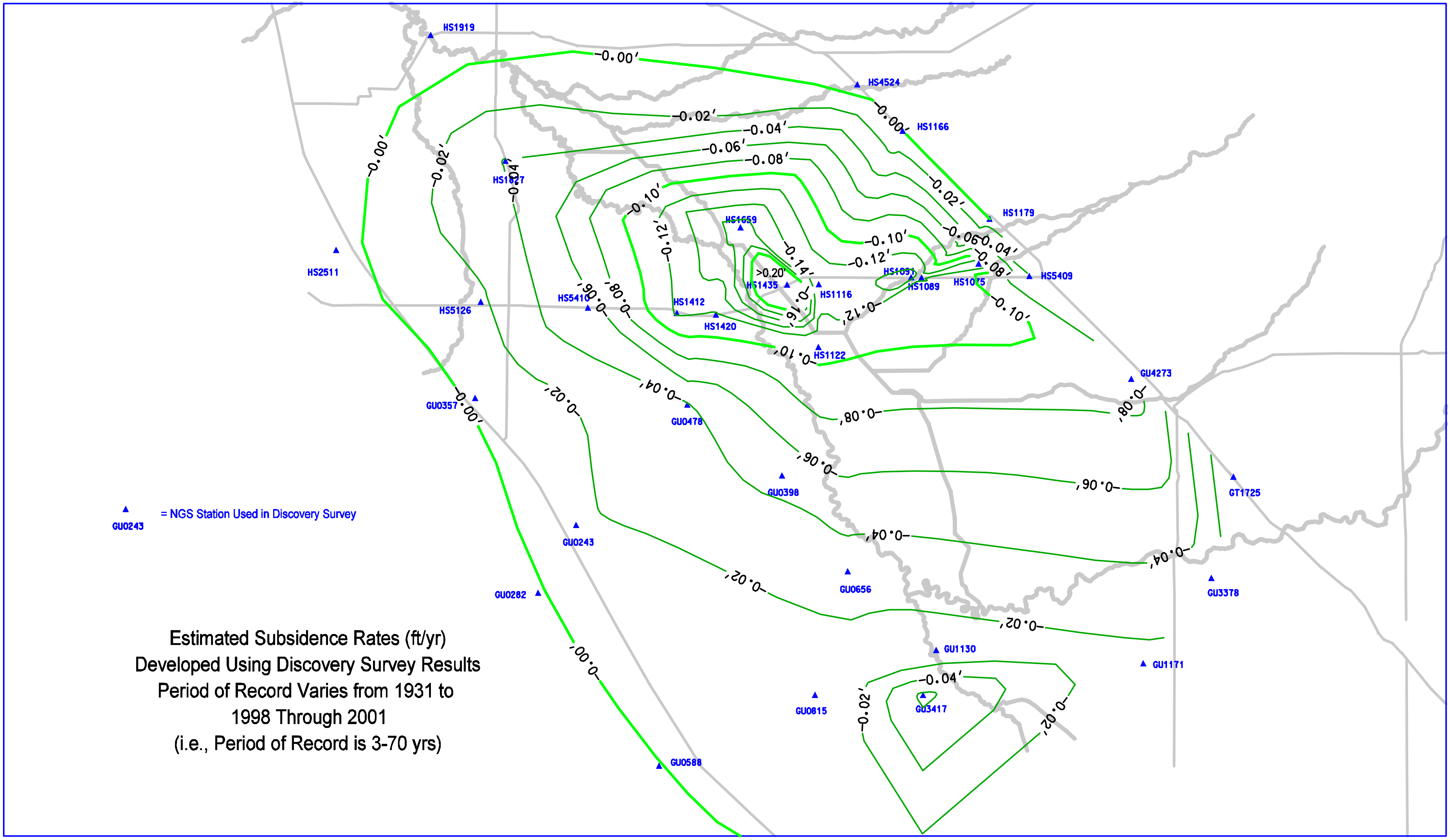

FIGURE 2 – ESTIMATED SUBSIDENCE RATES USING DISCOVERY SURVEY RESULTS

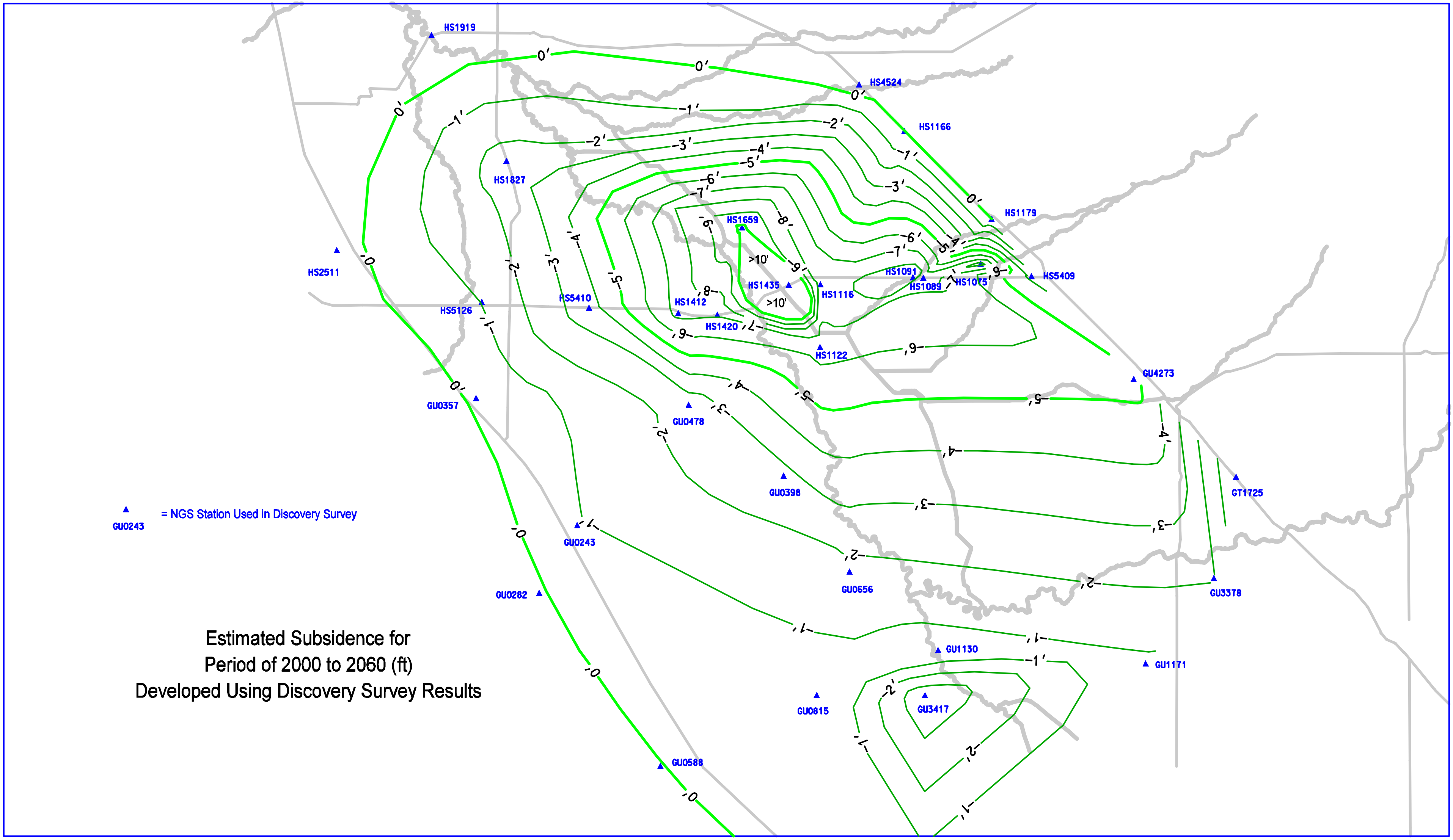

FIGURE 3 – ESTIMATED SUBSIDENCE FOR PERIOD OF 2000 TO 2060 USING DISCOVERY SURVEY

COMPOREHENSIVE STUDY INFORMATION PAPER:

TECHNICAL EVALUATION PROCESS

The purpose of this document is to describe how the various technical models or tools developed by the Comprehensive Study are used together to evaluate alternative scenarios and conditions. These tools include hydrologic, hydraulic, geotechnical, risk and economics. The tools can be used independently or in conjunction to perform various analyses. This document outlines the process by which information is passed between the tools to perform successive analyses and compare baseline and with-project results, the level of detail suitable to this type of analysis, and the assumptions inherent in the evaluation process.

COMPREHENSIVE STUDY TECHNICAL DATA AND TOOLS

There are four components to the technical evaluation process adopted by the Comprehensive Study:

- Synthetic hydrology
- Reservoir operation models (HEC-5)
- Geotechnical evaluation
- Hydraulic models (UNET, FLO-2D)
- Project Performance and Economics (FDA)

Information is passed between the various technical tools for any given condition or plan. The individual tools also provide information that may be used for numerous related but independent evaluations, such as reservoir reoperation or optimization, reach-specific hydraulics (such as channel capacity, scour potential, sediment transport, etc), and many others. The individual technical tools are described below, followed by a discussion of their role in the technical evaluation process.

Hydrology

Synthetic hydrology was developed for seven storm events (events with a 50%, 10%, 4%, 2%, 1%, 0.5%, and 0.2% chance of occurring in any year) for various storm centerings in the Sacramento and San Joaquin River basins. The five mainstem and 18 tributary storm centerings are based on patterns observed in gage data from historic events. The 30-day synthetic storm hydrographs are routed through the reservoir operations models to develop regulated flood hydrographs.

Reservoir Operations

HEC-5 reservoir operation models are used to simulate both headwaters reservoirs (upstream from the primary flood control reservoirs) and major flood control reservoirs in the Sacramento River and San Joaquin River basins. Unregulated, 30-day synthetic hydrographs are input to the reservoir operation models, which then simulate existing or proposed storage allocations, release schedules, objective flows, and other operational criteria. Two pairs of HEC-5 models are used, with one each in the Sacramento and San Joaquin River basins: headwaters HEC-5, and lower basin HEC-5. These models produce regulated hydrology (downstream from the major flood control reservoirs) that is used as input to the hydraulic models.

Geotechnical

A geotechnical analysis was performed to determine the stability and reliability of levees within the flood management system. A levee failure methodology was derived to determine at what elevation simulated flows could cause levees to fail. Levee reliability was simulated by developing a likely failure point (LFP) profile along both riverbanks on a reach-by-reach basis. The LFP represents the stage on the levee where there is a 50% probability of levee failure and is the basis for: identifying initial failure points in the levee, delineating floodplains, and determining in-channel stage-frequency relationships. The LFP is determined using the various levee failure curves that were developed to represent different levee conditions based on geotechnical data (soil type and geometry) and engineering judgment. The LFP elevation is used in the hydraulic models to trigger levee failures.

Hydraulics

The UNET hydraulic models cover the main channels and major tributaries of the Sacramento River and San Joaquin River. UNET is an unsteady, one-dimensional hydraulic model that uses detailed channel geometry and is capable of simulating weirs, bifurcations, storage, levees, and levee breaks. The upstream boundaries of the UNET models are where data are handed off from the hydrologic to the hydraulic analyses. Two-dimensional FLO-2D models were also developed for routing flood flows through large overbank and floodplain areas and are used to determine flood depth and extent (development of inundation areas for various flood frequencies). FLO-2D floodplain depths were also used to develop initial depth-damage relationships for economic evaluation, but FLO-2D is not used in the technical evaluation process for alternative plans. Hydraulic output from UNET is passed to the project performance and economic component in the form of stage- and discharge-frequency curves.

Project Performance and Economics

The Corps' primary model for performing flood damage reduction analysis is the Hydrologic Engineering Center's Flood Damage Reduction Analysis model (HEC-FDA, V 1.2), which integrates hydrologic, hydraulic, and geotechnical engineering and economic data. HEC-FDA incorporates uncertainty for risk-based analysis using a Monte-Carlo simulation procedure. Although HEC-FDA was designed to estimate urban flood damage, it was adapted for agricultural analyses. Each basin is divided into numerous economic impact areas that cover the valley floodplains and other flood-prone areas along the major tributaries.

The primary outputs of HEC-FDA that are used in project formulation and evaluation are project performance statistics and expected annual damages. Project performance statistics include the expected annual probability of flooding from all events in a given year, the long-term risk of flooding over specific time periods, and the conditional non-exceedence probability for specific events (probability of passing a specific flood event). Expected annual damage is calculated as the average or mean of all possible values of damage determined by Monte Carlo sampling of discharge-exceedence probability, stage-discharge, and stage-damage relationships and their associated uncertainties.

TECHNICAL EVALUATION PROCESS

An iterative process is used to evaluate plans using the Comprehensive Study's technical tools. Through an iterative process, the Comprehensive Study's technical tools are used to evaluate alternative plans. It is important that these tools in the same manner to evaluate alternative plans to ensure that the comparison of results both with existing conditions and other alternatives is valid. The existing condition results provide a baseline for comparison with other alternative plans or scenarios and the determination of their hydraulic and economic impacts. The flow of information involves initial evaluation by the hydrologic models, which pass flow data to the hydraulic models, which in turn pass flow frequency information to HEC-FDA. This process is outlined below in **Figure 1**, and described in detail in the following sections.

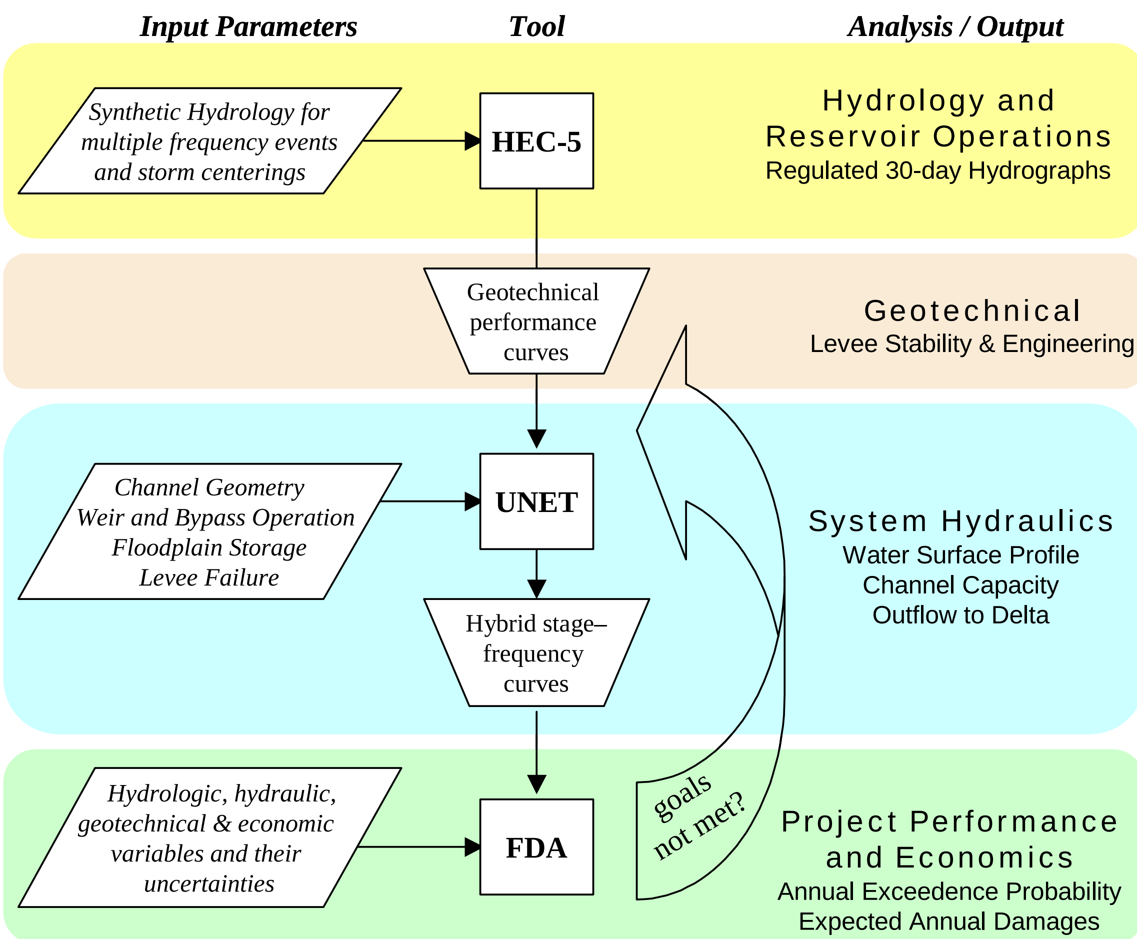

Figure 1 – Flow of Information Between Technical Tools

Hydrology and Reservoir Operations

Hydrology, in the form of 30-day unregulated hydrographs, is the starting point for any evaluation. Hydrographs are fed into the reservoir operations models to determine the impacts of existing storage facilities, expanding or reoperating existing facilities, or adding new storage facilities. The baseline hydrology is used if a plan or alternative does not include any changes to existing reservoir operations or storage. For each alternative, regulated hydrographs are developed for each of the seven storm events and each of the dominant storm centerings.

Geotechnical Performance

The chance of levee failure is represented through a geotechnical performance curve. This curve is the relationship between river stage and probability of geotechnical failure and is applied to each damage reach. The curves assume that damages can accrue in one of two ways: either the river stage becomes high enough to overtop the levee, or the stage rises significantly enough to cause geotechnical failure. The geotechnical performance of a levee depends on local soil conditions and construction and considers multiple modes of failure including under-seepage, through seepage, and strength instability.

The levee performance curves reflect a qualitative evaluation of the major geotechnical aspects of levee integrity. To define weak points within any particular reach, the likely failure points (LFP), probable non-failure points (PNP) and probable failure points (PFP) were defined along the reach's levee. The PNP is the water surface elevation at which levee failure becomes *highly unlikely*, and the PFP is the water surface elevation at which levee failure becomes *highly likely*. For this study, the PNP is the point at which the chance of failure is 15 percent and the PFP is the point at which the chance of failure is 85 percent. As described previously, the LFP represents the point at which the chance of failure is 50% and is used by UNET to trigger levee failure. The PNP, PFP and LFP values are based on the results of field investigations, past levee stability calculations, levee performance in the 1997 and 1998 flood events, and engineering judgment.

For geotechnical and structural analysis, the factors affecting uncertainty are rare flood stresses and loads, geologic properties of foundations, seepage through and below levees, construction materials (sand vs. clay), and maintenance practices. Uncertainty in structural performance occurs due to a levee's physical characteristics and construction quality. The geotechnical performance curves are used with the stage-frequency curves (see Hydraulics, below) to calculate performance and economics in HEC-FDA.

Hydraulics

The UNET hydraulic models route the regulated flood hydrographs through the system of tributary and mainstem channels in each basin for the various storm events and centerings. UNET is capable of reporting data at any of the thousands of cross sections in the models, but key index points have been chosen in each basin in order to make output analysis and handoff more manageable. Index points also provide the link between hydraulics and HEC-FDA (performance and economics).

The index point locations were chosen based on the first or initial breakout point within a river reach. In a given reach, this is the location where the first levee failure occurs in the baseline condition simulation, taking into account all storm centerings and frequencies. An index point is assigned to each economic impact area, providing a handoff point from UNET to HEC-FDA. For the baseline condition, the index point corresponds to the location where simulated flood damages would first begin to occur, representing the worst-case levee or bank condition within the reach. There are 62 index points in the Sacramento River Basin and 42 in the San Joaquin River Basin.

UNET modeling results are reported at each index point as a plot of event frequency versus water surface elevation. For example, the peak simulated water surface elevation produced by the various storm centerings for a 50-year flood event forms one point on the curve. Peak water surface elevations from UNET for the various centerings are plotted for each of the seven event frequencies and connected to form a stage-frequency curve.

For reaches with levees, the stage-frequency curve flattens or becomes horizontal at the point where the levee fails (at the LFP elevation). After failure, the water surface elevation remains relatively constant for all higher flow frequencies because flows are escaping into the floodplain through the levee break. The HEC-FDA model needs a complete stage-frequency curve to the top of the levee, so the upper end of the curve is extrapolated above the frequency of levee failure using the infinite-channel UNET run. The infinite channel run assumes that no levee breakouts occur (infinitely high LFP elevation) and that all water is contained within the main channels. The portion of the infinite channel frequency curve above the frequency of levee failure is translated down to meet the baseline (with-failure) curve where it intersects the LFP and flattens. The resulting hybrid curve, a combination of the with- and without levee failure scenarios, is then entered into HEC-FDA. Because no events less than a 2-year event are modeled, the slope of the curve between the 2-year and 10-year plot points is used to extend the curve downward to intersect the y-axis. The development of the hybrid stage-frequency curve is shown in **Figure 2**.

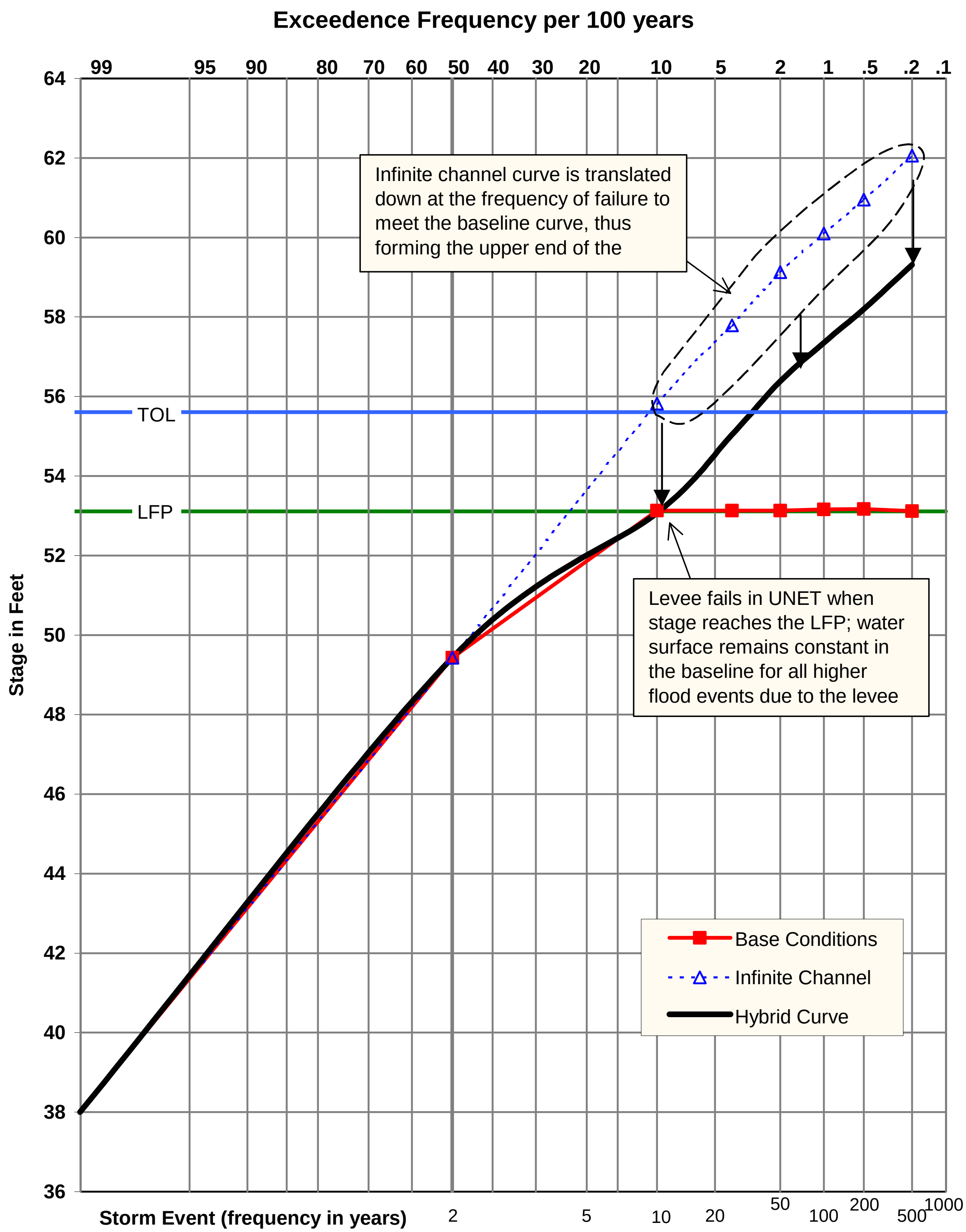

Figure 2 – Construction of the Hybrid Stage-Frequency Curve

Project Performance and Economics

FDA integrates input from the hydrologic, geotechnical and hydraulic technical tools in a risk-based analysis. Input data includes information relating to the uncertainty of the hydrologic data (such as period of record), levee performance curves, stage-frequency curves from UNET, and economic data (such as land use and property value). ***The primary outputs of HEC-FDA that are used in project formulation and evaluation are project performance and economic performance.***

A basic understanding of statistics and the Corps' risk and uncertainty practices is desirable in order to properly interpret the results from HEC-FDA. This section will provide a brief overview, but further reading materials are listed at the end of this document under Technical Resources. Exceedence probability reflects the probability that an event will occur or be exceeded in any given year.

Project Performance

The three primary project performance or flood risk results reported by HEC-FDA are annual exceedence probability, long-term risk, and conditional non-exceedence probability.

> **Annual Exceedence Probability (AEP):** AEP is a measure of the likelihood that an area will be flooded in any given year, considering the full range of floods that can occur and all sources of uncertainty (NRC 2000). For example, the 0.01 exceedence probability event has one chance in a hundred or a one percent chance of occurring in a given year. The 0.01 exceedence event is often misleadingly termed the 100-year event (by taking the inverse of 0.01), but it does **not** statistically represent an event that will occur once in 100 years. For instance, someone living in a 0.01 or 100-year frequency floodplain has a one in four chance of experiencing flooding during a 30-year period. Because the terms can be misinterpreted, several results from HEC-FDA are used to properly communicate flood risk.
>
> **Long Term Risk (LTR):** Long-term risk is the probability of damages occurring during a specified period of time. LTR is reported for 10-year, 25-year, and 50-year time periods. For example, a value of 0.850 for the 25-year reporting period reflects an 85% chance of flood damages during a 25-year period.
>
> **Conditional Non-Exceedence Probability by Events (CNE):** Conditional non-exceedence is the probability of safely containing an event with a known frequency, should that event occur. CNE is reported for the 10%, 4%, 2%, 1%, 0.4%, and 0.2% probability events. For example, a value of 0.04 for the 2% event corresponds to a four percent chance of passing the 2% or 50-year frequency flood.

Although these measures of risk seem similar, there are distinct differences between them. AEP accumulates all the uncertainties into a single value, whereas CNE is conditional on the severity of the flood event. Further, while AEP describes the likelihood that flooding *will occur*, CNE describes the likelihood that flooding *will not occur* during a given year (NRC 2000). Other agencies also use these measures of risk and uncertainty. For example, FEMA uses conditional non-exceedence in its certification criteria for levees, requiring a 90% probability of containing the 1% event.

Economic Performance

Economic performance is expressed in terms of expected annual damages (EAD). In a risk-based analysis, EAD is defined as the average or mean of all possible values of damage determined by Monte Carlo sampling of discharge-exceedence probability, stage-discharge, and stage-damage relationships and their associated uncertainties. It is calculated as the integral of the damage-probability function. EAD is used to calculate the Corps' National Economic Development (NED) objective (as described in USWRC 1983). NED is communicated as a ratio of project benefits to project costs and is commonly referred to as the B-C ratio.

ITERATION PROCESS

Iterations are performed within each analysis tool and between the tools until the planning goals or objectives are met. For example, successive iterations might be performed within UNET until a target water surface is achieved only to find that the risk target for that area was not met in HEC-FDA. In this case, additional iterations between UNET and HEC-FDA may be required until the risk target is also achieved. Adjustments may also be made directly to the stage-frequency curves, rather than going back to UNET, to fine-tune HEC-FDA results.

The number of iterations performed both within the models and between the models is largely dependent upon the type and number of planning objectives set for a particular plan and the level of detail desired. Initial simulations may be performed that examine only a few key index points to quickly narrow in on the targets; a final simulation examining all index points would be performed to refine the plan. Similarly, an expedited analysis process was developed to decrease the amount of time required to arrive at a plan that meets specified objectives. This expedited process is described below.

Expedited Analysis

Generating hybrid stage-frequency curves from the hydraulic models and passing this data to HEC-FDA is one of the most time-consuming steps in the technical evaluation process. During early iterations it may not be necessary or time-efficient to examine all index points and damage areas. As an alternative to generating stage-frequency curves and HEC-FDA output at all of the index points and corresponding damage areas in each basin, the index points and damage areas were grouped into larger, "bubble" areas for quick analysis. There are nine bubble areas in the Sacramento River Basin and seven in the San Joaquin River Basin, shown in **Figures 3 and 4**. One index point is chosen to represent all damage areas within a bubble area. The index point is chosen based on several factors including stage conditions, topography, initial breakout, and significance of damages caused. The hydrology and reservoir operation stages of the process do not change, and hydrographs from all frequency events are still run through UNET. Iteration is stopped when the HEC-FDA risk results are within an acceptable margin of either the baseline conditions or specific risk targets.

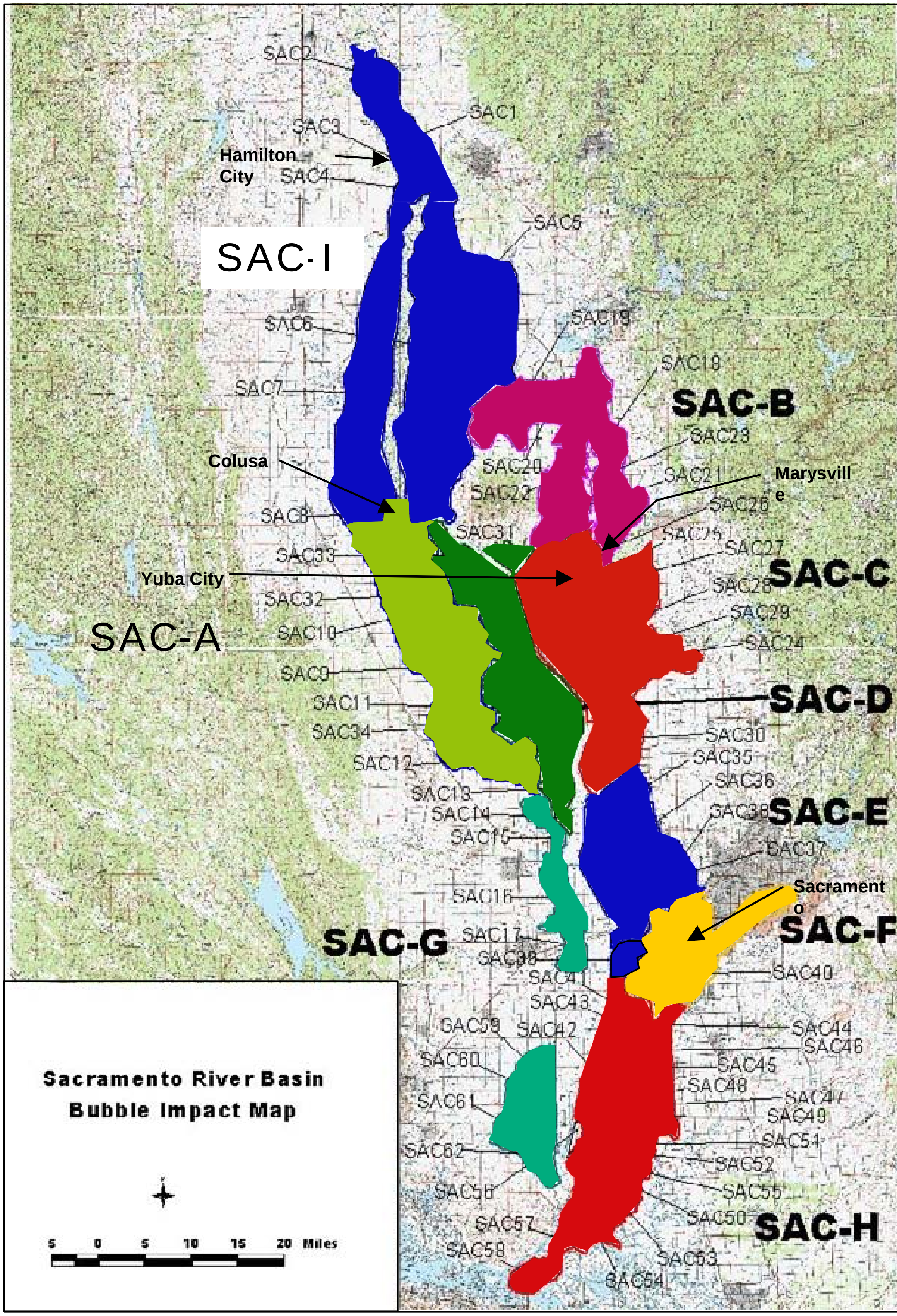

Figure 3 – Sacramento River Basin Bubble Impact Areas

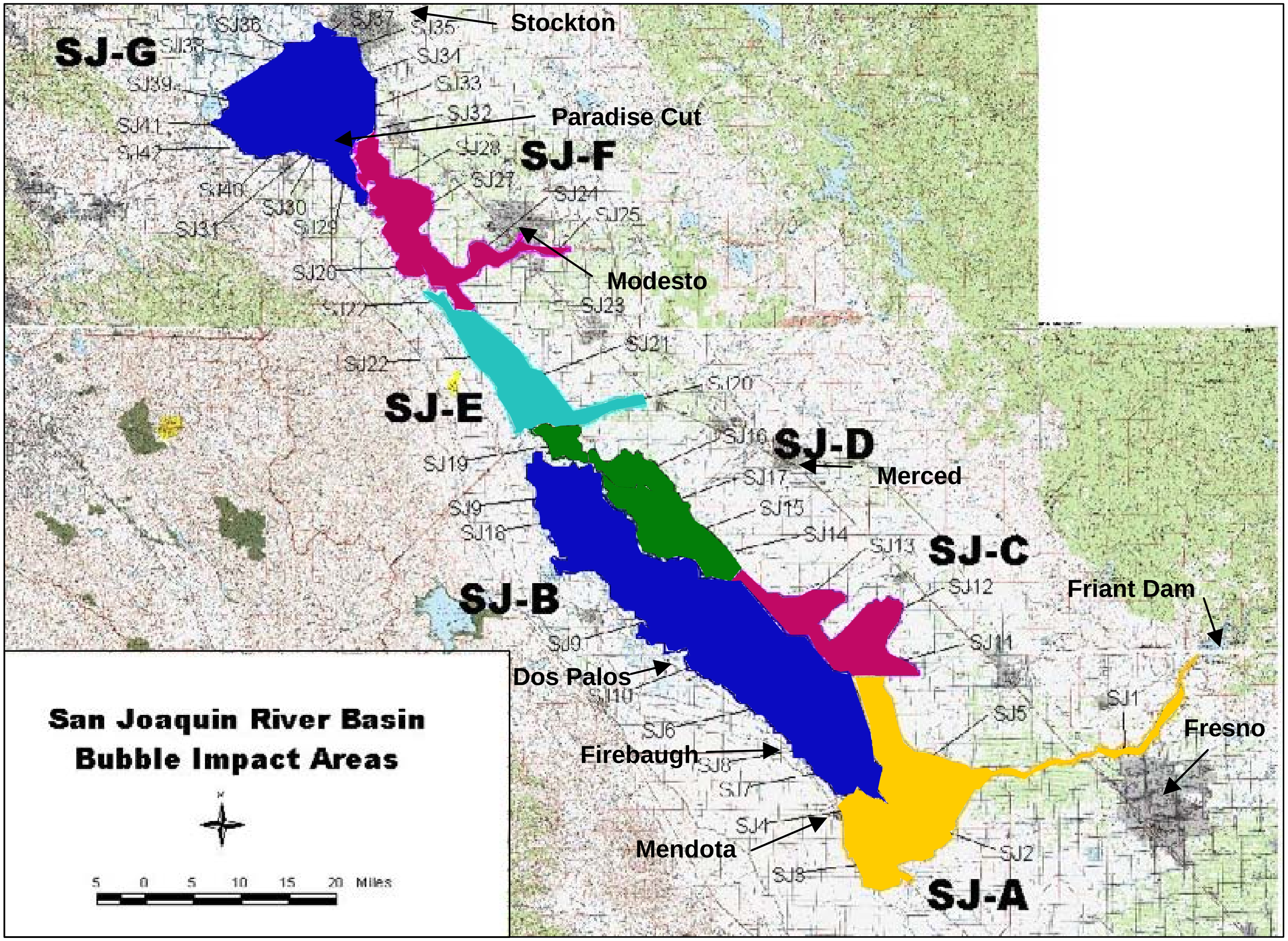

Figure 4 – San Joaquin Basin Bubble Areas

The expedited analysis process is suitable for comparing plans at a reconnaissance level and determining the size and extent of plan components. Because all index points are not evaluated there is a potential to over- or underestimate the success of an alternative in meeting plan goals. This level of accuracy is suitable for reconnaissance level master plan development and comparison because detailed feasibility and design studies would be performed on a regional basis should a plan be selected and implemented.

Achieving Plan Targets or Objectives

When evaluating results between UNET and HEC-FDA, it is important to remember that HEC-FDA applies uncertainty to all aspects of a plan. The HEC-FDA model takes into account the uncertainties associated with project hydrology (years of record available, reliability of records, accuracy of reservoir operations models), hydraulics (accuracy of UNET model and model input), and economics (accuracy of depth-damage estimates and economic input data). For example, passing a 100-year flow target in UNET may not be sufficient to achieve a 1/100 AEP or a high probability of passing the 100-year frequency event. This is because UNET does not consider the possibility that the computed 100-year water surface could be inaccurate.

Consider the case of a plan that proposes a new levee be constructed to pass a 50-year flow event and provide a CNE of at least 0.90 for the 2% exceedence event (90% chance of passing the 50-year frequency flood). UNET modeling is performed to determine the 50-year peak stage and the LFP of the new levee is set to this elevation. A stage-frequency curve is prepared for the index point in this reach and passed to HEC-FDA. The resulting CNE reflects only a 65% probability of passing the 50-year frequency event because the hydrology for this reach is based on only 40-years of gage record, introducing uncertainty. Fine-tuning of the stage-frequency curve indicates that an additional two feet will need to be added to the top of levee in order for the project to achieve the CNE target of at least 0.90 for the 2% exceedence event.

Comparing Results between Alternative Plans

Comparison of the HEC-FDA results for a particular plan with the baseline or without-project condition provides an indication of the success of the plan in terms of both economic savings (reduction in damages) and flood system project performance (frequency of flooding or flood risk). EAD can also be used to establish the benefit-cost ratio of an alternative. The estimated construction and implementation cost is compared with the economic savings (damages avoided) to provide a single B-C value for each plan. The higher the ratio of benefits to costs, the more desirable the alternative. When examining an array of alternative plans, the B-C ratio is useful in identifying the point of diminishing returns, or the point at which additional expenditures do not result in significant additional benefits.

TECHNICAL RESOURCES

National Research Council (NRC 2000) Risk Analysis and Uncertainty in Flood Damage Reduction Studies, National Academy Press, Washington DC

USACE (2000) *Design and Construction of Levees*, EM 1110-2-1913, U.S. Army Corps of Engineers (HQUSACE), Washington DC

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USACE (1998) *HEC-FDA Flood Damage Reduction Analysis,* User's Manual CPD-72, Version 1, U.S. Army corps of Engineers, Davis CA

USWRC (1995) *Engineering and Design – Introduction to Probability and Reliability Methods for Use in Geotechnical Engineering,* ETL 1110-2-547, U.S. Army Corps of Engineers (HQUSACE), Washington DC

USWRC (1983) *Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies*, Water Resources Council, U.S. Army Corps of Engineers, Washington DC

COMPREHENSIVE STUDY INFORMATION PAPER

VEGETATION AND FLOOD MANAGEMENT

The purpose of this document is to discuss how vegetation can impact the performance of the flood management system. This document presents information and preliminary findings developed during the course of the Comprehensive Study, but does not represent a detailed study of vegetation within the Sacramento and San Joaquin River flood control systems. While riparian vegetation has been identified as a vital component of successful environmental restoration in the Central Valley, vegetation can have both beneficial and negative impacts on flood management.

This document will address these key questions:

- Why is riparian habitat a critical element of environmental restoration?
- What are the impacts of vegetation on the flood management system?
- How can vegetation be successfully incorporated into flood management designs?
- What is the role of the Comprehensive Study?

Flood management and environmental improvement are dual objectives of the Comprehensive Study. The study seeks a balance between the vital roles that the rivers and waterways of the Central Valley play for both flood management and the environment. This paper identifies some ways in which habitat can be successfully incorporated into flood management plans, often benefiting the reliability or function of the flood management systems. However, the study recognizes that native vegetation restoration may not be appropriate in all portions of the flood management system.

WHY IS RIPARIAN HABITAT A CRITICAL ELEMENT OF ENVIRONMENTAL RESTORATION?

The question is often asked, "Why restore riparian habitat? Why not perform restoration elsewhere?" Riparian habitat is only found in transitional areas between aquatic and upland terrestrial habitats (Fischer and Fischenich, 2000). Riparian zones are unique, functional ecosystems that support an exceptionally diverse array of plants and animals. ***The ecological value and richness of riparian habitat is intrinsically linked to the direct connection with a river or watercourse.*** The presence of water, in an arid landscape, supports both plant and animal species and the dynamic nature of a river drives the natural succession of vegetation and other habitat in riparian communities. For this reason, the same biological diversity cannot be found in other areas, such as foothills or agricultural lands.

Prior to European settlement, riparian habitat lined our waterways with belts of vegetation several miles wide. The Central Valley alone held over 800,000 acres of riparian forest. ***Less than 5 percent of California's original riparian habitat exists today*** (Reclamation Board, 1988) and much of the remaining portions are disconnected and degraded in quality. Species that depend on riparian habitat, such as the Riparian Brush Rabbit and the Yellow-tailed

Cuckoo, continue to be added to both State and Federal Endangered Species listings. This trend indicates that remaining habitat is not enough to support sustainable populations of these species.

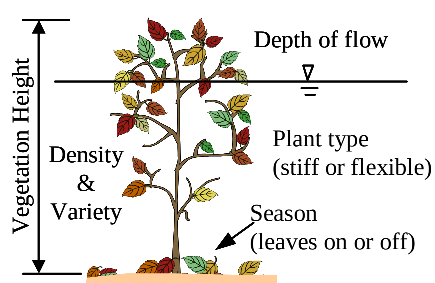
Many aquatic, terrestrial and avian animal species depend upon riparian systems for food, nesting habitat, and cover. These habitats often serve as migration corridors, such as the Pacific Flyway, and may be used by both terrestrial and avian species. As migratory birds move north in the spring and south in the fall along the flyway, they stop in riparian habitats to feed and rest during the long journey. While developed lands and agricultural fields do provide valuable habitat for some species, many rare, endangered, and endemic species live only in riparian areas.

Riparian areas perform other valuable functions in addition to supporting a unique ecosystem. Historically, wide riparian corridors and adjacent wetland areas improved water quality and sediment balance, regulating soil accretion and erosion, and allowing sediment deposition outside the main channel. They also attenuated flood flows, reducing peak flows and stages downstream.

IMPACTS OF VEGETATION ON FLOOD MANAGEMENT SYSTEMS

Vegetation can impact the performance of flood management systems in numerous ways, both positive and negative. For example, vegetation can reduce the ability for channels to carry flood flows, but can also prevent damaging erosion. ***The impact of vegetation on the flow carrying capacity of a stream depends upon the size of the channel and magnitude of flow, vegetation type and density, and location within the channel.***

Vegetation within a river channel causes drag, or a resistance to flow. Other sources of drag in river channels include rocks, boulders, soil conditions, and man-made obstructions such as bridges, docks, or pumps. The drag creates eddies and velocity gradients in the water, causing loss of momentum (Fischenich, 2000). Drag impacts are generally confined to the area immediately adjacent to the vegetation or other obstruction. Hence, the density and extent of vegetation are key factors in determining the degree of impact. Very dense vegetation located throughout a channel is likely to cause significant resistance and increase flood stage, whereas a narrow band of trees and shrubs parallel to the flow may have little impact on the channel's ability to carry flood flows. The impact of vegetation generally decreases as the depth of flow increases and the magnitude of the flood event increases. Hence, larger or deeper rivers tend to be less affected by vegetation and other obstructions than small streams and drainages.



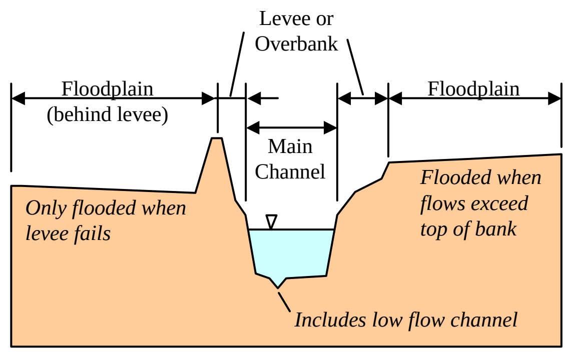
Factors influencing the impact of vegetation on flood flow

Vegetation density is influenced by the type of vegetation and the number, variety, and spatial arrangement of plants present. An orchard with orderly rows and managed undergrowth will have significantly less hydraulic impact than a natural riparian area containing a variety of plants of differing height, width, stiffness, distribution and density.

Vegetation with flexible stems, such as willows (*Salix* spp.) and herbaceous plants, can bend and flatten during high flows and may have little hydraulic impact. Woody shrubs and trees that have rigid stems will attempt to resist even high flows and can become significant obstructions; if they become uprooted, they also add to the damaging debris carried by flood flows.

The timing of a flood during the year also affects vegetation density. The influence of deciduous vegetation will vary by season, depending upon whether leaves are on (very dense) or off (less dense). ***In the Central Valley, flood events normally occur during the winter months when there is less vegetation present and deciduous plants have lost their leaves.*** However, late spring runoff floods can occur in both the Sacramento and San Joaquin River basins after leaves have re-emerged.

The impact that vegetation can have on flood flows is also related to where it is located, within the main channel, on levees or overbank areas, or within the floodplain, as shown in the figure at right.



Typical watercourse

The main channel is the primary flow-carrying portion of the waterway, generally the deepest part of the channel that also carries low or summer flows. Levees or overbank areas are immediately adjacent to the main channel; they help contain high flows and are generally above mean flow stages. The floodplain is located adjacent to the levees or overbank and only becomes inundated when banks or levees are overtopped, or a levee fails. For the case of a leveed channel, the floodplain may have no direct connection to the main channel except during extreme high flows or levee breach conditions.

Vegetation within the Main Channel

Vegetation located within the main channel of a river or flood management waterway can have the greatest impact on flow capacity, reducing flow velocity and increasing stage. Dense vegetation is rarely found within the main channel of large rivers because high flows typically remove all but the hardiest of young growth. Vegetation in the main channel may also be more likely to become uprooted due to higher flow velocities, adding to flood debris. While undesirable from a flood management standpoint, vegetation within main channels can be beneficial to aquatic species. Tree trunks and large woody debris provide habitat and protective cover for juvenile fish. Conversely, dense vegetation in the main channel that significantly reduces flow velocity and capacity can also adversely affect aquatic species by increasing water temperature and reducing dissolved oxygen during summer months.

Vegetation on Levees or Overbanks

Vegetation along channel overbanks or levees is inundated less often than vegetation in the main channel, typically becoming a factor only when water surface elevation exceeds the top of bank or impinges on a levee. Vegetation along channel overbanks or levees may trap debris or reduce flow velocity immediately adjacent to the banks, but has less impact on flow in the main channel. For this reason, vegetation in this zone has less impact on larger watercourses, such as the Sacramento River, but can significantly impede flow in small or narrow streams.

Large trees with large, shallow root systems, particularly non-native species like eucalyptus, can be damaging to levees due to their size, weight, or destructive root systems. Large trees are generally not advisable on levees, although they may be allowed on berms. Certain types of vegetation along overbanks or levees can be beneficial in terms of reducing erosion and stabilizing the channel banks. Large vegetation along the banks also provides shaded riverine aquatic cover, which is essential to aquatic species at the critical water-land interface and is also very beneficial to many avian and terrestrial species. Water quality and fishery resources are also enhanced by the reduction in water temperature resulting from shade cover.

Low vegetation can reduce flow velocities immediately adjacent to the bank, minimizing levee scour, wavewash, and bank erosion. The fibrous root systems of certain types of native and non-native vegetation, such as rye grasses (*Elymus* spp.) and various shrubs, can also have a stabilizing effect on loose bank soils and further reduce the potential for erosion. A vegetated berm or overbank buffer zone that is removed from the main channel can benefit the reliability of the flood management system by protecting the levee. Lower velocities present in wide, vegetated overbank areas can also encourage sediment deposition outside the main channel.

Vegetation along levees is often removed or otherwise managed as part of routine flood management system maintenance. This practice prevents large vegetation that may harm the integrity of the levee from becoming established and facilitates visual inspection of the levee during emergencies. However, vegetation management often destroys beneficial plants also, and reduces valuable riparian habitat. Extreme management measures, such as burning, can remove low-lying protective vegetation cover and expose levees to erosion.

Vegetation in the Floodplain

Water moving through floodplain areas is generally shallower and slower than in the main river channel. For this reason, floodplains of sufficient size can provide temporary storage and effectively attenuate high flows, changing the timing and duration of flood peaks. Flood attenuation is a decrease in the volume of water as it moves downstream, resulting in lower peak flow. The natural function of a floodplain is to attenuate rather than convey flows, and floodplain vegetation plays a part in reducing flow velocity, trapping flood debris, and encouraging sediment deposition. However, the majority of floodplain lands within the Central Valley are disconnected from the river by levees and no longer provide any flood management benefits.

Floodplain lands are highly fertile because of their historic interaction with the river, which deposited sediments and replenished soils during floods. A healthy river ecosystem depends on the interaction between the river and floodplain for sediment deposition and vegetation succession. When a floodplain is connected to a river, vegetation provides valuable terrestrial habitat and can improve wildlife survival during flood events.

INCORPORATING VEGETATION INTO FLOOD MANAGEMENT IMPROVEMENTS

Vegetation can play many roles when incorporated into the design of a flood management system. Table 1 illustrates the relative benefits of different types of riverside vegetation.

TABLE 1

RELATIVE EFFECTIVENESS OF SPECIFIC VEGETATION TYPES

	Effectiveness of Vegetation Type		
Benefit Provided by Vegetation	***Herbaceous***	***Shrub***	***Tree***
Stabilizes bank erosion	Medium-High	High	Medium
Traps sediment	High	Medium	Low
Filters nutrients, pesticides, microbes	Medium-High	Low	Low-Medium
Provides shaded riverine aquatic cover	Low	Medium	High
Provides wildlife habitat			
Range/pasture/grassland	High	Medium	Low
Forest	Low	Medium	High
Provides visual diversity (aesthetics)	Medium	Medium	High
Provides bank stabilization	Low-Medium	Low	Medium
Provides flood conveyance	High	Low	Low-Medium

Source: Modified from Fischer and Fischenich (2000)

When properly incorporated into a flood management project, vegetation can be beneficial in preventing soil erosion and scour during flood events. Vegetation reduces flow velocity and armors the soil surface, while the roots bind the soil and act as a stabilizer (Fischenich, 2001). Vegetation contributes to water quality by filtering nutrients, agricultural compounds, and other elements from runoff entering the watercourse. Large vegetation provides shade, which can decrease water temperatures and have a beneficial impact on fishery resources.

However, the negative impacts of vegetation must also be taken into consideration when incorporating vegetation into flood management design, including the impact on flow capacity, contribution to flood debris, and ability to inspect levees during floods. ***One of the keys to successfully incorporating vegetation into flood channel design is allowing sufficient width between levees or confining terraces to accommodate both flood management and environmental improvements.*** In this way, planned vegetation can be allowed to grow within portions of the levees or confining terraces without impacting function of the flood management system, at the same time providing erosion and attenuation benefits. However, this can be difficult to accomplish on a local scale without significant changes to the flood management system. In these cases, smaller vegetative design components may be the most effective way to incorporate vegetation into existing flood management systems.

Vegetative Design Components

The following discusses several methods of maximizing the benefits of vegetation while minimizing negative impacts on the flood management system. These methods include vegetated buffer strips, riparian flood corridors, and vegetative bank protection.

One method of maximizing the benefits of vegetation is to develop a ***vegetated buffer strip*** between a levee that is susceptible to erosion and the main channel. A narrow buffer strip, parallel to the flow, can have little impact on flood flow while improving levee reliability by significantly reducing the scour velocity along the levee or bank. A buffer strip requires a relatively small amount of land and can reduce the need for riprap or rock bank protection in some cases. Vegetated buffer strips can also reduce costly environmental mitigation requirements and reduce constraints put on routine vegetation maintenance on the adjacent levee. Vegetated buffers can also be established along waterside stability berms.

Another method is to incorporate a ***riparian flood corridor*** in the flood management system. A riparian flood corridor differs from a buffer strip in that it is generally wider, supports the movement or dispersal of organisms, and connects two or more larger habitat areas. Riparian flood corridors support greater plant diversity and have more significant environmental value and potential. But a flood channel with a riparian corridor must be designed with sufficient width to accommodate high flows and offset any stage impacts due to the vegetation. Riparian flood corridors should also be wide enough to allow natural sedimentation and degradation processes without endangering levees, and prevent undesirable sediment accumulation. Riparian flood corridors are best implemented on a regional because they can involve significant changes to a flood management system.

Large rock or riprap is a common and effective form of bank protection along river channels of the Sacramento and San Joaquin River basins. Riprap forms a barrier between high velocity flood flows and levee soils, armoring the bank with its bulk and weight. While effective, riprap is costly to transport and place, both economically and environmentally, and prevents the growth and establishment of native riparian vegetation. In some cases, soil deposition on riprap above the normal water line may allow the establishment of limited vegetation without affecting the function of the bank protection.

Biotechnical bank protection and ***soil bioengineering*** can be viable alternatives to riprap erosion protection in some cases. These methods utilize vegetation in combination with organic and man-made materials to protect channels and banks. There are various types of biotechnical erosion control treatments, including root wads, organic soil mats and fiber nets, vegetated cribwalls, brush mats, and live woody materials or wattling. Although the use of biotechnical bank protection has been somewhat limited on large river systems and may not be appropriate in all applications, it can be highly effective when combined with other flood management and environmental restoration measures and is gaining popularity throughout the United States. The Columbia River is an example of effective, large-scale use of biotechnical bank protection and riverbank bioengineering. Biotechnical methods are often less expensive than traditional erosion control techniques, require less maintenance, and can significantly reduce mitigation requirements.

Planning for Dual Objectives: Flood Management and Environmental Restoration

Flood management designs that incorporate vegetation should recognize that what represents an effective buffer strip in hydraulic terms does not necessarily represent a functioning riparian system in ecological terms. For this reason, projects should clearly define both the flood management and environmental improvement goals. The ways in which vegetation can be incorporated will depend on many factors, including: the magnitude of flood flows; area geology, soils, and geotechnical issues; the type of plants or wildlife habitat targeted for restoration; economic concerns; landowner and community concerns; adjacent land use; and climate conditions. These issues will differ from location to location, as will project goals and objectives. For example, certain reaches of the San Joaquin River only carry water during flood events. Because water is not available throughout the growing season, these reaches may not be able to support beneficial vegetation under current conditions. Elsewhere, environmental conditions may spur aggressive vegetation growth well beyond the intentions of the project, requiring careful monitoring and clearly defined maintenance practices to prevent negative impacts to the flood management function of the river system. For these reasons, careful planning and design is required when incorporating vegetation into multi-purpose project designs.

WHAT IS THE COMPREHENSIVE STUDY'S ROLE?

The Comprehensive Study has the task of finding ways for flood management and environmental values to coexist. The Comprehensive Study is using three methodologies to accomplish this task. First, the Comprehensive Plan will include guiding principles that emphasize the dual nature of the study and place value on the incorporation of environmental objectives into the design of future flood management facilities. These principles will ensure that future projects weigh both the flood management and environmental goals and examine the river system as a single, functioning unit. Second, the Comprehensive Study will document important lessons learned and knowledge developed during the study, such as the information included in this paper. Third, the study has developed system-wide tools for evaluating hydraulics and ecosystem function to support future project design. These tools will ensure that both goals can be fully measured, evaluated, and achieved.

The Comprehensive Study has developed hydraulic models covering the channel and overbank areas of the major rivers and tributaries in the Sacramento and San Joaquin River Basin. ***The hydraulic models are capable of simulating different types and densities of vegetation in terms of their contribution to channel roughness.*** The hydraulic models can be used to determine how vegetation affects the flow carrying capacity of a river channel. The Study also developed an ecosystem function model that can be used to predict the types of habitat that might be expected when changes are made to the flood management system. These and other resources are valuable tools for designing future flood management projects and evaluating the impact of vegetation and environmental improvements within the flood management system.

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